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INTEGRATION OF GENERATIVE DESIGN AND BIM TECHNOLOGIES IN ARCHITECTURAL DESIGN: STATE OF THE ART AND FUTURE DIRECTIONS

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The present article offers a comprehensive review of the evolution, current state and future prospects of integrating generative design methods with Building Information Modelling (BIM) technologies over the period from 2010 to 2025. Against the backdrop of the global digital transformation of the architecture, engineering and construction (AEC) industry, a convergence can be observed between algorithmic approaches to form-finding and semantically rich BIM databases. Based on a systematic analysis of academic literature, technical reports and real-world case studies – including projects by Zaha Hadid Architects and complex healthcare and sports facilities – the study examines the transition from parametric modelling to multi-objective optimisation and the emerging adoption of generative artificial intelligence (GenAI). Particular attention is paid to technical aspects of interoperability (Rhino.Inside.Revit, APIs, IFC), data management issues in accordance with the ISO 19650 standard, as well as ethical and professional challenges associated with the automation of creative processes. The article demonstrates how generative algorithms are transforming the role of the architect from a form-maker into a curator of the design solution space, and analyses the potential of large language models (LLMs) for automating code compliance checking and the generation of design solutions.

Keywords
Generative design; Building Information Modelling (BIM); Architectural design; Parametric modelling; Computational design; Workflow integration; Performance-based design; Digital twin; ISO 19650; Artificial intelligence in architecture.

1. Introduction

1.1. Paradigm shift in architectural design

The architectural industry in the first quarter of the twenty-first century is characterised by an unprecedented pace of technological change, which fundamentally redefines both the professional toolkit and the ontology of design practice [1]. The traditional drawing-based model of Computer-Aided Design (CAD), in which digital lines acted as a direct equivalent of analogue strokes, had by the 2010s given way to Building Information Modelling (BIM). BIM shifted the focus from geometric representation to information management, whereby each element of the model is endowed with attribute data specifying its physical, functional and operational characteristics [2][3].

However, as BIM was being implemented, a significant problem became apparent: a rigid data structure and a strong orientation towards documentation frequently became an obstacle at the early, creative stages of design. BIM platforms, which are highly effective for coordination and the production of construction documentation, often proved insufficiently flexible for conceptual exploration and experimental form-finding [4][5]. In parallel, the field of computational design was developing, enabling the creation of complex geometries and the automation of routine operations, yet it often existed separately from the building information environment, generating a persistent "data gap" between concept and realisation.

Between 2020 and 2025 the industry entered a phase of active integration of these two methodologies. Generative design (GD) ceased to be a niche instrument of avant-garde offices and began to be embedded into standard workflows through its integration with BIM. This made it possible not only to automate drafting, but also to delegate to the computer the process of searching for optimal solutions within predefined constraints, marking a transition towards a paradigm of human–machine "co-authorship" in design [6][7].

1.2. Terminological framework and conceptual boundaries

For an accurate analysis of the subject matter it is necessary to clearly demarcate a number of key concepts which are often used as synonyms in professional discourse, although they differ in nature and methodology.

Parametric design is a process based on algorithmic thinking, in which relationships between elements are defined through explicit parameters and rules. A change in an input parameter (for example, storey height or the rotation angle of a module) leads to a predictable and deterministic reconfiguration of the entire system [8][9]. As Patrik Schumacher notes, parametricism has become a dominant style that enables the management of complex curvilinear geometry and adaptive components; however, it requires the architect to fully understand and construct the underlying logical dependency tree [10][11].

Generative design, in contrast to parametric design, is oriented towards outcomes rather than the step-by-step construction process. The architect specifies objectives (for example, minimising evacuation distances) and constraints (site footprint, budget), while the system, using evolutionary algorithms (such as genetic algorithms), independently generates hundreds or thousands of design alternatives and performs their selection and optimisation [6][12]. Here, the computer acts not as a drafting tool but as a generator of novelty, capable of proposing solutions that may be non-obvious to the human designer [13].

Generative artificial intelligence (GenAI), which has rapidly developed in the period 2023–2025, represents the next stage in this evolution. Unlike generative design, which is grounded in explicit rules of physics and geometry, GenAI relies on probabilistic models—such as large language models and diffusion models—trained on massive datasets to synthesise new solutions. GenAI can operate with unstructured data (text, images) and "hallucinate" novel forms based on latent patterns in the training corpus, creating new opportunities for creativity while simultaneously introducing risks related to reliability and verifiability [14][15].

1.3. Relevance and problem statement

The integration of generative methods into the BIM environment addresses a number of critical challenges in contemporary architecture, ranging from the rationalisation of complex geometries for digital fabrication to the optimisation of a building's environmental performance. However, this process is associated with numerous technical and methodological challenges. These include issues of interoperability (compatibility of data formats), the difficulty of managing very large sets of generated design alternatives, the need to adapt existing standards (such as ISO 19650), and a high entry threshold for professionals, which presupposes programming and computational design skills [16][17].

The aim of this article is to provide a comprehensive analysis of the current state of integration between generative design and BIM, to identify the key technologies that enable this coupling, and to assess the impact of these processes on architectural practice. We examine how theoretical concepts are implemented in large-scale projects, which barriers hinder their widespread adoption, and what new horizons are opened by the application of artificial intelligence in the near future.

2. Research methodology

This review is based on a systematic analysis of sources published between 2010 and 2025, covering journal articles, conference proceedings (CIB W78, eCAADe), technical documentation issued by software developers (Autodesk, McNeel) and reports from leading architectural practices.

2.1. Material selection strategy

The selection of materials was carried out according to their relevance to the topic of convergence between computational design and Building Information Modelling. Priority was given to sources that contained:

- Empirical data: descriptions of real-world implementation cases, covering project stages from concept design through to construction (up to LOD 400).

- Technical analysis: detailed discussion of algorithms, scripts and software architectures (for example, the operation of Rhino.Inside.Revit or NSGA-II algorithms).

- Comparative studies: evaluations of the effectiveness of different optimisation approaches (genetic algorithms versus machine learning techniques).

In total, more than 130 sources were included in the review [18][19], which makes it possible to construct a representative picture of the state of the field. The time frame 2010–2025 was chosen in order to trace the evolution from the emergence of early visual programming plug-ins to the latest experiments with neural networks.

2.2. Structure of the analysis

The analysis is structured along three key vectors:

- Technological vector: examination of tools and platforms (Dynamo, Grasshopper, RIR, AI agents).

- Process vector: analysis of changes in workflows, data management within a Common Data Environment (CDE) and relevant standards.

- Applied vector: assessment of the outcomes of these technologies in specific architectural typologies (facades, layouts, master planning).

3. Results: technological evolution and practical implementation

3.1. Tool ecosystem: from fragmentation to seamless integration

The history of integrating generative design and BIM can be described as a

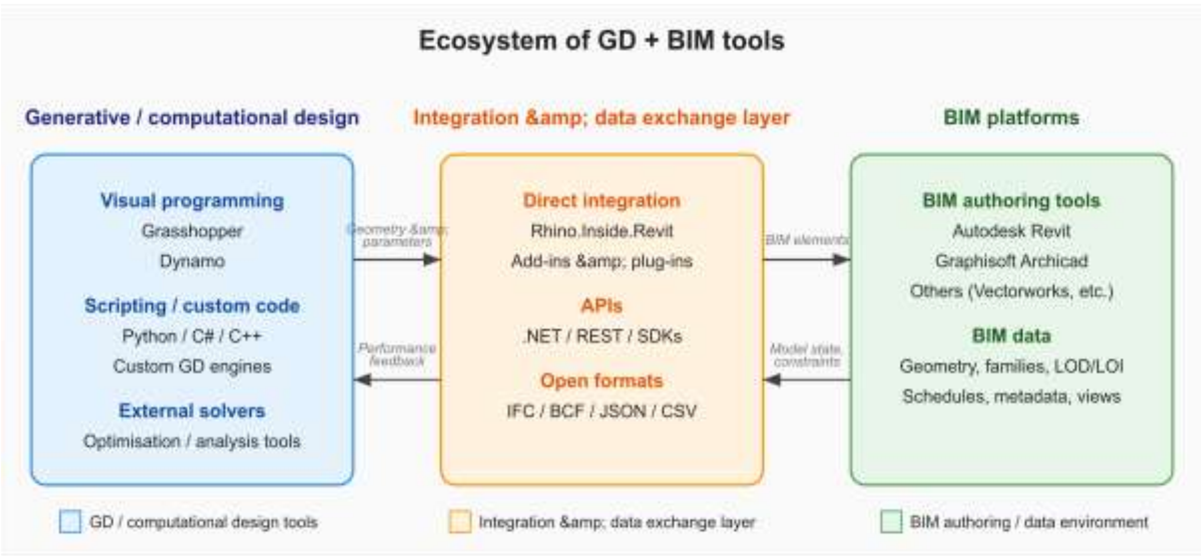

Figure 1. Ecosystem of generative design and BIM tools

gradual shift from file-based exchange to direct connections via application programming interfaces (APIs).

3.1.1. The era of visual programming (2010–2018)

Until the mid-2010s, the main barrier for architects was the need to write textual code (C#, Python) in order to automate tasks within BIM environments. The emergence of visual programming tools (visual programming languages, VPL), such as Dynamo for Revit and Grasshopper for Rhino, democratised access to algorithmic design [5][20].

Dynamo enabled users to create scripts (graphs) by connecting nodes with wires in order to manipulate geometry and data in Revit. This opened up opportunities for:

- Automation of routine tasks: batch renaming of sheets, automated creation of views, and placement of elements based on coordinates imported from Excel [21][22].

- Parametric modelling: construction of complex geometries (for example, twisted towers) driven by mathematical formulae with subsequent conversion into BIM elements [23].

- Initial optimisation: the integration of genetic algorithms (via Project Refinery, later Generative Design in Revit) made it possible to conduct design space exploration (optioneering) directly within the BIM environment [24].

However, at this stage the “data handover” problem persisted. Grasshopper, which led in advanced form-finding, and Revit, which dominated in documentation, remained largely separate worlds. The transfer of geometry through SAT, IFC or DWG formats often resulted in the loss of parametric behaviour and semantic information, turning “smart” walls into “dumb” geometric bodies (BREPs) that were unsuitable for further parametric editing in BIM [16].

3.1.2. The Rhino.Inside.Revit revolution (2019–2025)

The emergence of Rhino.Inside.Revit (RIR) marked a turning point by effectively removing a major interoperability barrier. RIR makes it possible to run the Rhino and Grasshopper cores directly inside the Revit process and memory address space as an add-in. This represents not merely data exchange but a fusion of execution environments [16].

Key advantages of RIR identified in the literature include:

- Direct access to the API. Grasshopper scripts can call the Revit API directly to create, delete and modify native elements (walls, slabs, families) in real time, bypassing intermediate file-based workflows [26][27].

- Bidirectionality. Changes made to geometry in Rhino can be propagated instantly to the Revit model, and conversely, parameters from Revit can be used as input data for generative scripts in Grasshopper.

- Hybrid workflows. Architects gained the ability to exploit Rhino's powerful geometric libraries (for example, for unrolling double-curved surfaces) while simultaneously leveraging Revit's documentation and coordination tools. This has become the de facto standard for the design of complex facades and bespoke structural systems [28][29].

3.2. Task typologies and case study analysis

The literature review makes it possible to distinguish several principal application domains in which integrated GD+BIM technologies have demonstrated the greatest effectiveness.

3.2.1. Rationalisation of complex geometry

One of the most challenging tasks in contemporary architecture is the transformation of conceptual free-form geometry into a physically buildable structure. In this context, generative algorithms act not so much as form creators as tectonic optimisers.

Case: Morpheus Hotel (Zaha Hadid Architects)

The Morpheus Hotel in Macau has become a canonical example of algorithmic rationalisation. The building features a unique free-form exoskeleton that performs both structural and expressive functions.

- Problem. The geometric complexity of the exoskeleton made the use of traditional 2D drawings practically impossible. It was necessary to design and fabricate cladding for the exoskeleton and glazing, including areas with pronounced double curvature [30].

- Solution. Engineers from Buro Happold and Front employed parametric models in Rhino/Grasshopper to analyse and rationalise the surface. More than 30 distinct façade systems were identified. In the free-form zone around the atria, the surface was subdivided into 242 unique rhomboid macro-panels.

- Algorithmic optimisation. Custom scripts were used to analyse the curvature of each panel. Wherever feasible, double curvature was approximated by flat or singly curved (cylindrical) elements in order to reduce fabrication costs. For areas with extreme curvature, the scripts generated data for bespoke manufacturing.

- Link to fabrication. The model served not only for visualisation but also as a direct source of production data. Each panel was assigned a unique identifier and coordinates of its fixing nodes, which were transmitted to the factory. Installation accuracy was ensured by pre-assembling panels on the ground and lifting them into place as larger blocks [30][31].

Case: The Oval (Limassol)

Another illustrative example is the high-rise project The Oval in Limassol, Cyprus.

- Methodology. The firm SEAMLEXITY developed a comprehensive computational framework for the panelisation of the double-curved shell. The envelope was subdivided into thousands of aluminium panels.
- BIM integration. The parametric model controlled the entire process: from material nesting optimisation through to the generation of G-code for CNC machines. This made it possible to realise a complex free-form geometry within a stringent budget by minimising the number of unique substructure types and panel sizes [32][33][34].

3.2.2. Functional and spatial optimisation

Generative design enables the optimisation of spatial layouts on the basis of quantitative performance metrics.

Case: Autodesk Office in Toronto (MaRS project)

This project became a pilot demonstrator for the potential of multi-objective layout optimisation.

- Input data. Data were collected from employees regarding their work preferences (need for quiet, requirement for communication), along with the geometric constraints of the existing building [6][35].
- Objective functions. The algorithm optimised the layout against several conflicting criteria: "Buzz" (level of social activity), "Views" (quality of external views), "Daylight" (availability of natural light) and "Adjacency" (proximity of teams).
- Process. More than 10,000 layout alternatives were generated. The design team (The Living) used scatter plots to navigate the design space and to select solutions lying on the Pareto front, i.e. options representing optimal trade-offs between the different objectives.
- Result. The selected option provided a balance between privacy and communication that would have been effectively unattainable through manual trial-and-error. It is important to emphasise that the AI system did not "make the decision"; rather, it supplied a set of alternatives for expert evaluation by the architects [7][36].

Healthcare facilities and stadiums

In hospital design, generative algorithms are used to minimise staff travel distances and optimise logistical flows. One study [37] describes the automatic generation of a healthcare facility layout that accounts for both routine operation and emergency situations, including infection control requirements.

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In stadium design (for example, the Hangzhou Tennis Center), parametric scripts are employed to generate the seating bowl. The algorithm automatically calculates the C-value (a visibility parameter) for each spectator seat, optimising the rake of the stands and the roof geometry to ensure visual comfort and protection from precipitation [38][39].

3.2.3. Environmental optimisation and wind comfort

The integration of simulation engines such as EnergyPlus and OpenFOAM into generative design workflows makes it possible to optimise building form with respect to microclimatic performance.

One study [40] reports the use of generative design for optimising pedestrian wind comfort. By varying the shape and relative placement of towers, the algorithm was able to reduce areas with uncomfortable wind conditions by 11.9% and areas with dangerous wind conditions by 9.7% compared with the baseline configuration. This demonstrates that building form can become not merely an aesthetic gesture but the outcome of computations targeting aerodynamic efficiency.

3.3. Data management and standards (ISO 19650)

Внедрение генеративных процессов создает серьезные вызовы для управления данными. Генерация тысяч вариантов (optioneering) приводит к взрывному росту объема файлов и метаданных. Стандарт **ISO 19650** становится критически важным инструментом для упорядочивания этого хаоса в Среде Общих Данных (Common Data Environment, CDE) [41] [42].

The implementation of generative processes poses significant challenges for data management. The generation of thousands of alternatives (optioneering) leads to an explosive growth in the volume of files and associated metadata. The ISO 19650 standard thus becomes a critically important instrument for structuring this "chaos" within a Common Data Environment (CDE) [41][42].

3.3.1. Structuring generative data

According to ISO 19650, every information container must have a unique identifier. However, traditional naming conventions (Project–Originator–Zone–Level–Type–Role–Number) are not always adequate when dealing with thousands of generative design iterations.

- Adaptation of naming conventions. Recent studies propose using the "Number" field or additional metadata to encode generative parameters (for example, generation number and individual ID in a genetic algorithm). This makes it possible to trace the "lineage" of each design variant [42][43].

- Approval statuses. It is crucial to distinguish between data that are in a "Work In Progress" state (draft scripts, intermediate generations) and "Shared" data (validated options for coordination with other disciplines). The use of a CDE enables automated version control and helps prevent obsolete or erroneous generative models from being used downstream in production [44][45].

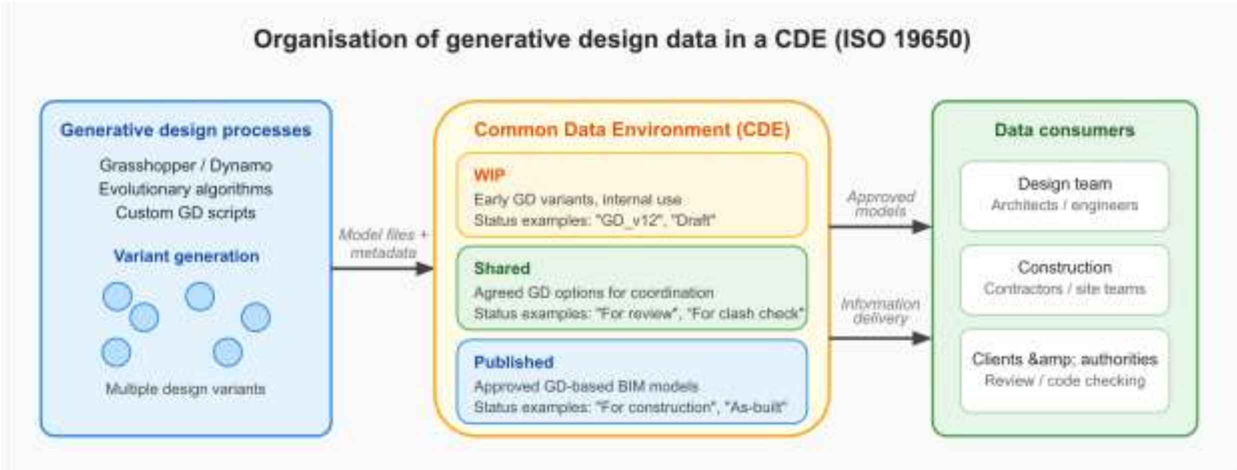

Figure 2. Schematic organisation of generative design data within a Common Data Environment (CDE) according to ISO 19650.

3.3.2. Data quality

The "garbage in, garbage out" principle is fundamental in the context of generative design. Errors in the underlying BIM model (for example, unclosed room boundaries or incorrect material assignments) lead either to failed generations or to misleading optimisation results. Consequently, preliminary data validation becomes a mandatory stage of the workflow, ensuring that input models meet the minimum quality requirements before they are used in GD processes [19][46].

4. Prospects: the era of artificial intelligence (2023–2025)

If the previous decade was largely devoted to algorithmic optimisation, the current period is characterised by the integration of deep learning methods and

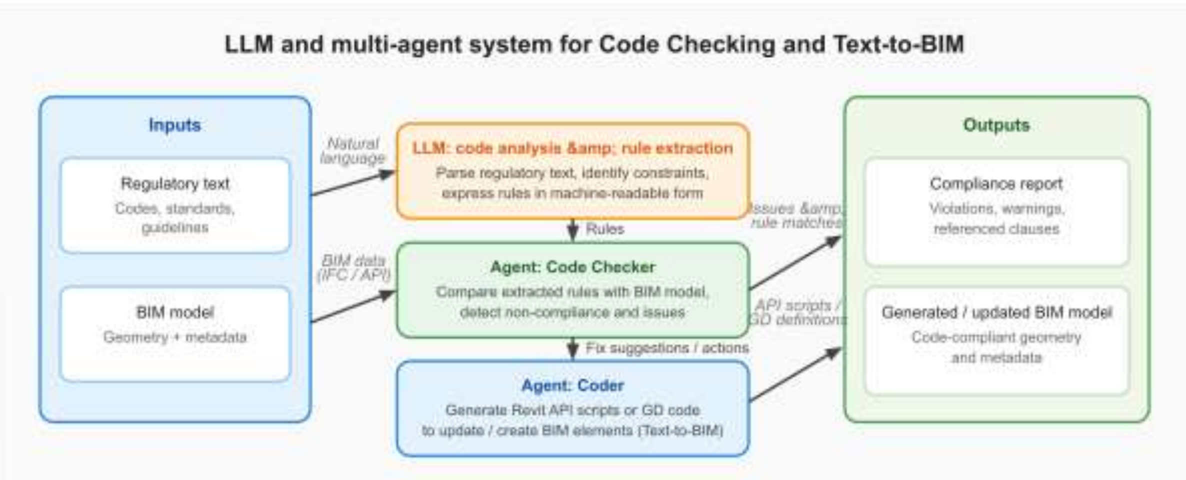

Figure 3. Conceptual workflow using an LLM and multi-agent system for automated code checking and Text-to-BIM generation.

large language models (LLMs) into design and BIM-centred workflows.

4.1. LLMs for automated code checking

Traditional automated code compliance checking has required a labour-intensive translation of textual building regulations (e.g. SNiP, GOST, international building codes) into machine-readable rule sets, typically expressed as explicit if–then conditions.

- Breakthrough. The use of large language models (LLMs) such as GPT-4 enables semantic analysis of regulatory texts and automatic extraction of rules. One study [47] presents a framework in which an LLM extracts constraints from bridge design specifications and transforms them into queries to a knowledge graph representing the BIM model.

- Results. The precision of this approach reaches 84.4%, which is significantly higher than for purely manual methods, although expert verification is still required. LLMs are capable of interpreting complex nested conditions and contextual dependencies that were largely inaccessible to rigid rule-based systems of the previous generation [1].

- Educational dimension. Experiments conducted in North American universities show that students can effectively use LLMs to identify code violations in Revit models; however, they encounter difficulties when "debugging" AI hallucinations and formulating sufficiently precise prompts (prompt engineering) [1].

4.2. Text-to-BIM and multi-agent systems

One of the most ambitious directions is the generation of full-fledged BIM models from textual descriptions (Text-to-BIM). In contrast to text-to-image generation, where visual artefacts are tolerable, BIM requires precise topology and construction logic. For a comparison of key characteristics, see Table 1.

- Multi-agent approach. Studies published in 2024 propose the use of systems composed of several AI agents. For example, one agent (Planner) decomposes the task into sub-tasks; a second agent (Coder) writes Python scripts for the Revit API; a third agent (Reviewer) checks the code for errors; and a fourth agent (Executor) runs the validated code within the BIM environment [49].

- Advantages. This approach helps to circumvent the lack of very large BIM model datasets for end-to-end training, since the model generates construction code rather than geometry directly. As a result, the system produces parametric, editable models instead of "dead" meshes, thereby maintaining the core advantages of BIM and generative design workflows [49].

Table 1. Comparative analysis of approaches to design automation

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No	Characteristi	Parametric design	Generative design)	Generative artificial ligence (Generative AI)
1.	Logic	Deterministic (rule-d)	Evolutionary (goal- and tion-based)	Probabilistic (data-en pattern learning)
2.	Input data	Parameters and ulae	Constraints and tive functions	Prompts (text / images)
3.	Mechanism	Explicit modelling of ionships	Genetic algorithms GA-II and others)	Neural networks (LLMs, sion models)
4.	Transparency	"White box" (full rol and pretability)	"Grey box" (evaluation ics are understandable)	"Black box" (reasoning outputs are difficult to ain)
5.	Role within	Creation of adaptive lies	Optimisation of layouts building volumes	Code checking, Text-to- workflows, eptual/early-stage hing
6.	Example	Adaptive façade l	Multi-objective nisation of Autodesk S office layouts	Generation of a Python t for the Revit API via -4

5. Discussion

5.1. From explicit to implicit design

The integration of generative design and artificial intelligence marks a fundamental epistemological shift: a transition from explicit modelling, in which the architect manually defines each line and relationship, to implicit modelling, in which the architect manages the space of possibilities and the evaluation criteria. This transformation alters the very nature of authorship. In the MaRS Office project, the author of the layout is neither the human nor the algorithm alone, but their interaction. The architect becomes a "designer of meta-systems", defining how the building should be designed rather than prescribing in detail what the building should be [35][50].

5.2. Economic efficiency and DfMA

The use of generative methods demonstrates a high return on investment, particularly when integrated with Design for Manufacture and Assembly (DfMA) principles. The ability, at early design stages (around LOD 200), to anticipate fabrication complexity and to optimise geometry for specific manufacturing capabilities (as in The Oval project) makes it possible to save millions of dollars in materials and logistics. Automated generation of fabrication drawings (spool drawings) and schedules reduces the labour required for documentation by an estimated 30–50% [51][52]

5.3. Challenges and limitations

Despite notable achievements, there remain significant barriers to widespread adoption:

- Hallucinations and reliability. The probabilistic nature of Generative AI is unacceptable for safety-critical engineering calculations. Robust mechanisms for stringent verification and validation of AI-generated results are required.
- Data proprietorship. The lack of open, high-quality datasets of BIM models constrains the training of specialised neural networks. In contrast to textual corpora, BIM models are typically treated as commercially sensitive assets.
- Skills gap. The industry faces an acute shortage of professionals who combine architectural expertise with programming and computational design skills. Universities are only beginning to adapt their curricula to include training in prompt engineering and working with APIs [1][53].

6. Conclusion

Over the past fifteen years, the integration of generative design and BIM technologies has evolved from theoretical experimentation to an integral component of the design process for complex projects. The current state of the field is characterised by the maturity of visual programming tools (Dynamo, Grasshopper) and the successful overcoming of interoperability barriers through solutions such as Rhino.Inside.Revit.

Generative algorithms have demonstrated their effectiveness in tasks of geometric rationalisation, functional optimisation and environmental analysis, enabling the creation of buildings with higher performance characteristics and distinctive aesthetics. The implementation of the ISO 19650 standards provides the necessary framework for managing increasingly complex data flows.

Future developments beyond 2025 are inextricably linked to the deployment of artificial intelligence. The symbiosis of deterministic BIM algorithms, which ensure precision and regulatory compliance, with probabilistic AI models, which contribute creativity and semantic analysis, promises a radical increase in architectural productivity. However, this will require not only technological retooling, but also a revision of educational curricula, legal frameworks and the underlying philosophy of architectural creativity. The future of architecture lies not in replacing the human designer with the machine, but in creating a form of hybrid intelligence capable of addressing problems of previously unattainable complexity.

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