

(REVIEW ARTICLE)



FROM STATIC CAD TO DYNAMIC DIGITAL TWINS: A SYSTEMATIC REVIEW OF DATA-EXCHANGE FRAMEWORKS IN INDUSTRY 4.0 MANUFACTURING

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ABSTRACT

Industry 4.0 is transforming Computer-Aided Design (CAD) from a largely static engineering representation into a potential source of structured information for connected manufacturing systems. CAD is used to capture the geometry, topology and tolerances of a design along with materials and design intent, but it is not itself the changing operational condition of a physical asset. Digital Twins overcome this limitation by connecting digital models with physical products, machines or processes via sensing, industrial communication, analytics and feedback. The presented Systematic Literature Review follows the PRISMA 2020 guidelines and synthesizes the exchange formats used to facilitate the transition from static CAD to dynamic Digital Twin in manufacturing. It takes a look at file-based and neutral product-model standards, application programming interfaces, industrial communication protocols, semantic models, Asset Administration Shells, Product Lifecycle Management systems, Manufacturing Execution Systems and digital-thread architectures. An eight-dimensional taxonomy of the literature is developed, based on exchange mechanism, interoperability level, Digital Twin maturity, lifecycle phase, model fidelity, synchronisation frequency, interface architecture and digital/physical creation sequence. The synthesis demonstrates that geometric translation alone is not enough for a functional Digital Twin Engineering meaning. Asset identity, Asset versions, Process context, Data quality, Synchronisation and Cyber security are also essential for a successful integration. Proprietary formats, semantic heterogeneity, legacy equipment, lack of lifecycle traceability, skills gaps and limited ability to validate in the operational environment are persistent challenges. In developing industrial economies, evidence from Southern Africa indicates that enabling technologies exist but interconnection is often weak, exacerbated by these challenges. The review hence suggests a multi-layered reference architecture consisting of CAD and PLM to store the design intent, interoperability mechanisms to enable the exchange of contextualized data, industrial systems to feed the operational data and the Digital Twin to sustain monitoring, prediction, optimization and engineering decision making.

Keywords: CAD; Digital Twin; Industry 4.0; Interoperability; STEP; Asset Administration Shell; OPC UA; Digital thread; smart manufacturing; Data Exchange; Developing economies.

1 INTRODUCTION

Digital engineering and the information systems are used in the modern manufacture to design products, plan production, control equipment and manage product information. Computer-Aided Design (CAD) is used to design and modify a product's geometry, dimensions, materials, assembly, and engineering specifications, while Computer-Aided Manufacturing (CAM) will utilize engineering information to support process planning, tooling, machining, and computer numerical control (CNC) programming. These technologies, when combined, have allowed for greater design accuracy and manufacturing repeatability, as well as the efficiency of engineering activity (Petrenko, 2025).

Nevertheless, engineering information is typically spread out among various software arrangements and industrial systems. A CAD model can be used to define the planned geometry and properties of a component, but it cannot be used to represent the current operating condition, production performance, maintenance history and quality status of the physical asset. Instead, the operational information is stored in Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA) systems, Manufacturing Execution Systems (MES), maintenance databases and production records (Sobociński et al., 2024). This division results in the broken and disjointed nature of information and loss of continuity throughout the product's life cycle. Industry 4.0 has made the world of connected engineering systems, sharing information between design, manufacturing, operation and maintenance, more relevant than ever. All of these – Product Lifecycle Management (PLM), concurrent engineering and the digital thread – are interested in linking information from different lifecycle stages. Digital Twin technology is an extension of this by establishing a link between a physical product, machine or process and a digital representation, by using data acquisition and communication, modelling and analysis (Grieves and Vickers, 2017).

Potential benefits include real time monitoring, predictive maintenance, process simulation, production optimisation, fault diagnosis and informed engineering decisions. However, these benefits rely on heterogeneous systems being able to exchange and interpret information consistently (Zeid et al., 2019). The lack of integration of CAD data into a dynamic Digital Twin environment is due to differences in file format, data structure, identifiers, communication protocols, and information semantics. This can happen in technologized economies.

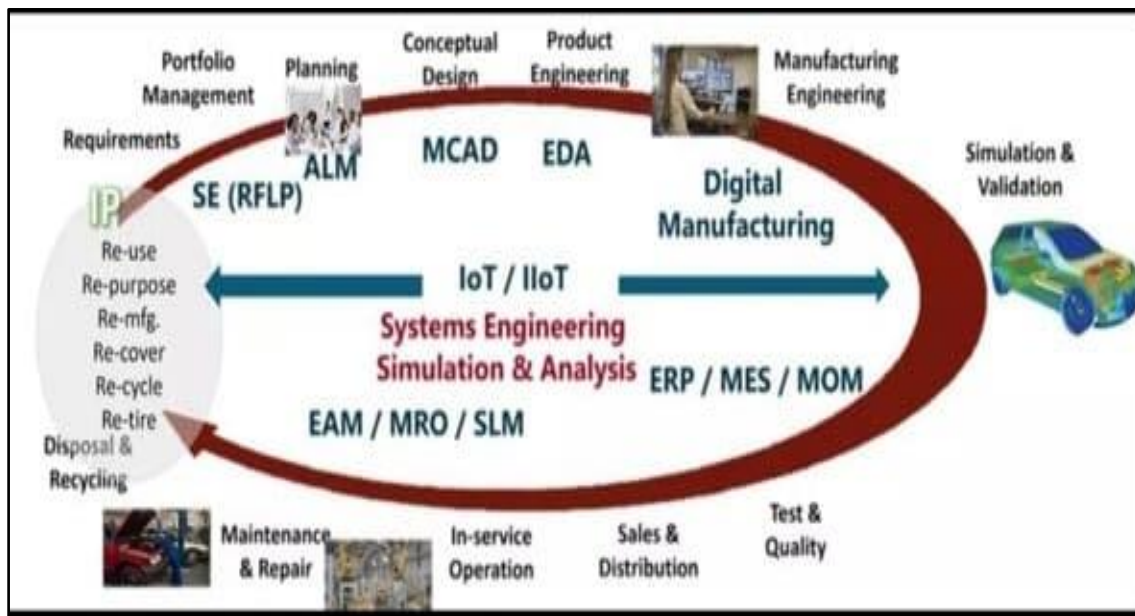


Figure 1: Systems engineering, simulation and analysis across the product lifecycle.

A study of 18 manufacturing companies in Zimbabwe revealed several Industry 4.0 technologies in use in organisations but not interconnected and optimised, coupled by high solution cost and lack of supporting public policy (Muhla et al., 2025a). The capability of reconfiguration of operations in a timely and efficient manner in response to market uncertainties regarding demand and volatility, which is heavily dependent on timely and trustworthy information flows, was still underdeveloped in a parallel study of 20 manufacturers in Zimbabwe (Muhla et al., 2023). A study of the region also identifies the deficit of skills in automation, data and digital technologies, and the role of learning factories in cultivating practical skills needed in the connected manufacturing domain (Ndiyamba et al., 2026). Organisation ability and context are as much a part of data exchange as technical standards.

While a few reviews have focused on Digital Twins (Zeid et al., 2019; Strohmeier et al., 2022; Liepert et al., 2026), the route from static CAD models to dynamic operationally connected twins has been discussed separately, and even fewer

reviews have considered this pathway in brownfield and resource constrained environments. This review fills that void. It has three impacts: (i) a PRISMA-suggested synthesis of data-exchange frameworks between CAD, PLM, simulation, manufacturing systems and Digital Twins; (ii) an eight-dimensional taxonomy of comparison of the data-exchange frameworks; and (iii) a layered reference architecture and a research agenda that explicitly considers the development of industrial economies.

2 BACKGROUND AND THEORETICAL FOUNDATIONS

2.1 Product lifecycle information and the digital thread

A product lifecycle includes design, engineering analysis, process planning, manufacturing, inspection, operation, maintenance, modification and disposal (Horsthuis and Lutters, 2024). Each stage provides information that could be needed by other stages. Design activities produce geometry, dimension, tolerances, materials and assembly data; manufacturing activities produce process data, machine conditions, quality records and maintenance histories. Accurate, traceable and continuous information exchange is thus essential to effective lifecycle management.

Manufacturing information is typically spread across the CAD system, CAM system, PLM system, MES system, SCADA system, PLCs, sensors and maintenance databases and may take various formats, identifiers, data structures and communication protocols (Sobociński et al., 2024). When not integrated, information is duplicated, fragmented, or hard to trace. For instance, a CAD system might have the design specification of a machine part, a PLC might record the operating conditions of the machine part, and a maintenance system might store the failure records of the machine part. If these sources are not connected, then engineers have difficulty associating equipment failures with the characteristics of equipment design, manufacturing or operating performance.

The digital thread tackles this challenge by creating a connected flow of information between the design data and manufacturing, inspection, operational and maintenance data, creating better configuration management, traceability and the capacity to see the impact of a change at one life cycle stage on another.

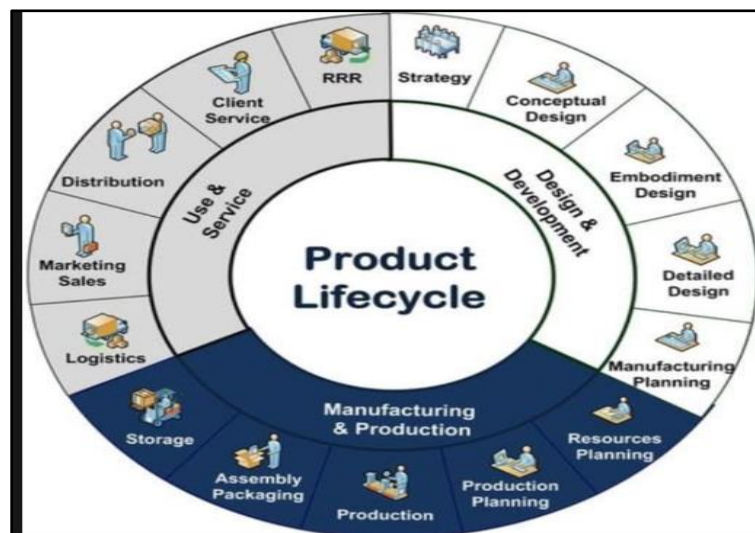


Figure 2: Stages of the product lifecycle.

2.2 From CAD model to Digital Twin

A Digital Twin is based on connected lifecycle information. In general, a digital replica of a physical product, machine, process or production system that is linked to data about the associated conditions, behavior and changes of the physical entity. Some of the foundational discussions are by Glaessgen and Stargel (2012), Grieves (2014), and Grieves and Vickers (2017). Whilst a CAD model is mainly about what an asset is designed to be, a Digital Twin aims to portray how the asset exists, functions, and evolves over time (Dawkins and Kitchin, 2025). A twin can be used to integrate CAD geometry, PLC information, sensor data, operational records, maintenance history, analytics and simulation (Gebhard and Wang, 2026).

The distinction between the direction and automation of data flow is one of the most widely used distinctions, provided by Kritzinger et al. (2018). The exchange of data is manual in a digital model, in a digital shadow, only data flow from the physical to the digital object, and in a Digital Twin, data flow in both directions, with the influence of the digital

object on the physical object. This distinction is relevant to the present review since many systems referred to in the literature as Digital Twins are, when examined more closely, digital models or a digital shadow.

2.3 Interoperability and enabling technologies

Being interoperable is a key ingredient in the transformation of CAD to Digital Twin. Data exchange is defined as the ability of applications to share data with databases, machines and platforms (Zhao et al., 2024), while interoperability is characterized by the capacity of these systems to interpret and correctly use the data they share. There are several different aspects of interoperability: technical, syntactic, semantic, organisational, and lifecycle (Liepert et al., 2026).

There are a number of technologies that enable this integration. Product-model exchange is enabled by the STEP (ISO 10303) and related standards. OPC Unified Architecture (OPC UA) and industrial data communication and information modelling (Vesela et al., 2025) and MQTT supports lightweight publish/subscribe messaging (Soni and Makwana, 2017). Application programming interfaces (APIs) and middleware link software applications (Basavapura Jayaprakash, 2025), and ontologies and semantic models enable the maintenance of the meaning of engineering information (Strohmeier et al., 2022). The concepts of Asset Administration Shell (AAS) offer structured digital representations of industrial assets. A product-model standard can describe geometry well, but not convey real-time data, and an industrial communication protocol can convey real-time data but not describe geometry well.

The practical effect on the ground is seen even in day to day engineering projects. For the design of a passive upper limb exoskeleton, for instance, three concept designs were created in SolidWorks and imported into Ansys for structural simulation purposes; the carbon fibre and nylon variants were compared in terms of the deformation, stress, and factor of safety (Tandi et al., 2025). A vertical-axis wind turbine used for highway slipstream energy harvesting was evaluated using similar CAD-to-analysis workflows, with the focus on its aerodynamics and computational fluid dynamics (CFD) characteristics (Muyambo et al., 2025). In both, geometry was successfully transferred from tool to tool, but the resulting models were one-way design artefacts that did not have a lasting connection to the operating asset. They are a representation of the initial point of the CAD-to-twin pathway, the digital model, not the end.

3 METHODOLOGY

3.1 Aim and research questions

The aim of this review is to examine how data-exchange frameworks enable the integration of static CAD information with operational and lifecycle data in dynamic Digital Twin environments for Industry 4.0 manufacturing. Four research questions (RQs) guided the review:

- **RQ1.** Which data-exchange frameworks, standards and architectures are used to connect CAD, PLM, simulation, manufacturing systems and Digital Twins?
- **RQ2.** What interoperability challenges arise when engineering information is transferred across the product lifecycle?
- **RQ3.** Which technologies support technical, syntactic, semantic and organisational interoperability in Industry 4.0 manufacturing?
- **RQ4.** What limitations, research gaps and future opportunities are reported in the literature?

3.2 Review design and information sources

The study used a systematic literature review design as it is a systematic approach that has been well designed to identify, screen, appraise and synthesize relevant literature in a planned and transparent manner (Cooper et al., 2018). Reporting is in line with the PRISMA 2020 statement (Page et al., 2021). This information source comprises Scopus, Web of Science, IEEE Xplore and ScienceDirect, which have engineering, manufacturing, automation, computer science and Industry 4.0 research. Google Scholar was used as an additional resource for identifying seminal publications and grey literature, with backward and forward citation searching further identifying key publications.

3.3 Search strategy

The search strategy was designed based on four concepts: Digital Twins, engineering models, data exchange and manufacturing. Within each concept, synonyms and related terms were combined together by using the Boolean operators OR; across concepts the Boolean operators OR were combined with the AND operator, as illustrated in Table 1. The search strings were modified according to the syntax of the respective databases and used with titles, abstracts and keywords.

Table 1: Search concepts and representative keywords.

Search concept	Representative keywords	Purpose
Digital Twin	"digital twin" OR "digital replica" OR "virtual representation"	Identify studies concerning digital representations connected to physical entities.
Engineering models	"CAD" OR "computer-aided design" OR "digital model" OR PLM	Capture engineering and lifecycle information sources.
Data exchange	"data exchange" OR interoperability OR "data integration" OR "information integration"	Identify integration mechanisms and interoperability challenges.
Manufacturing context	manufacturing OR "smart manufacturing" OR "Industry 4.0" OR production	Limit the review to relevant industrial environments.

3.4 Eligibility criteria

Studies were selected against the inclusion and exclusion criteria in Table 2.

Table 2: Inclusion and exclusion criteria.

Criterion	Included	Excluded
Publication type	Peer-reviewed journal articles, conference papers, review papers and authoritative technical standards where relevant.	Editorials, advertisements, opinion pieces and non-technical webpages.
Publication period	Primarily 2016–2026, with earlier seminal works retained where directly relevant.	Publications outside the period without clear foundational relevance.
Subject relevance	CAD, CAM, PLM, Digital Twins, data exchange or interoperability in manufacturing.	Studies unrelated to engineering information, manufacturing or Digital Twin integration.
Technical content	Frameworks, architectures, standards, platforms, interfaces and integration challenges.	Studies with no meaningful discussion of data exchange or system integration.
Language	English-language publications that can be reliably interpreted.	Publications that cannot be reliably assessed.
Availability	Full-text publications accessible for screening and appraisal.	Records with insufficient information for assessment.

3.5 Study selection

Retrieved records were exported to a reference-management system and duplicates were removed. Titles and abstracts were then screened against the eligibility criteria, and potentially relevant papers underwent full-text assessment, with the reasons for exclusion documented at each stage. The flow of records through identification, screening and inclusion is summarised in the PRISMA flow diagram in Figure 3, which was prepared following the PRISMA 2020 template (Haddaway et al., 2022).

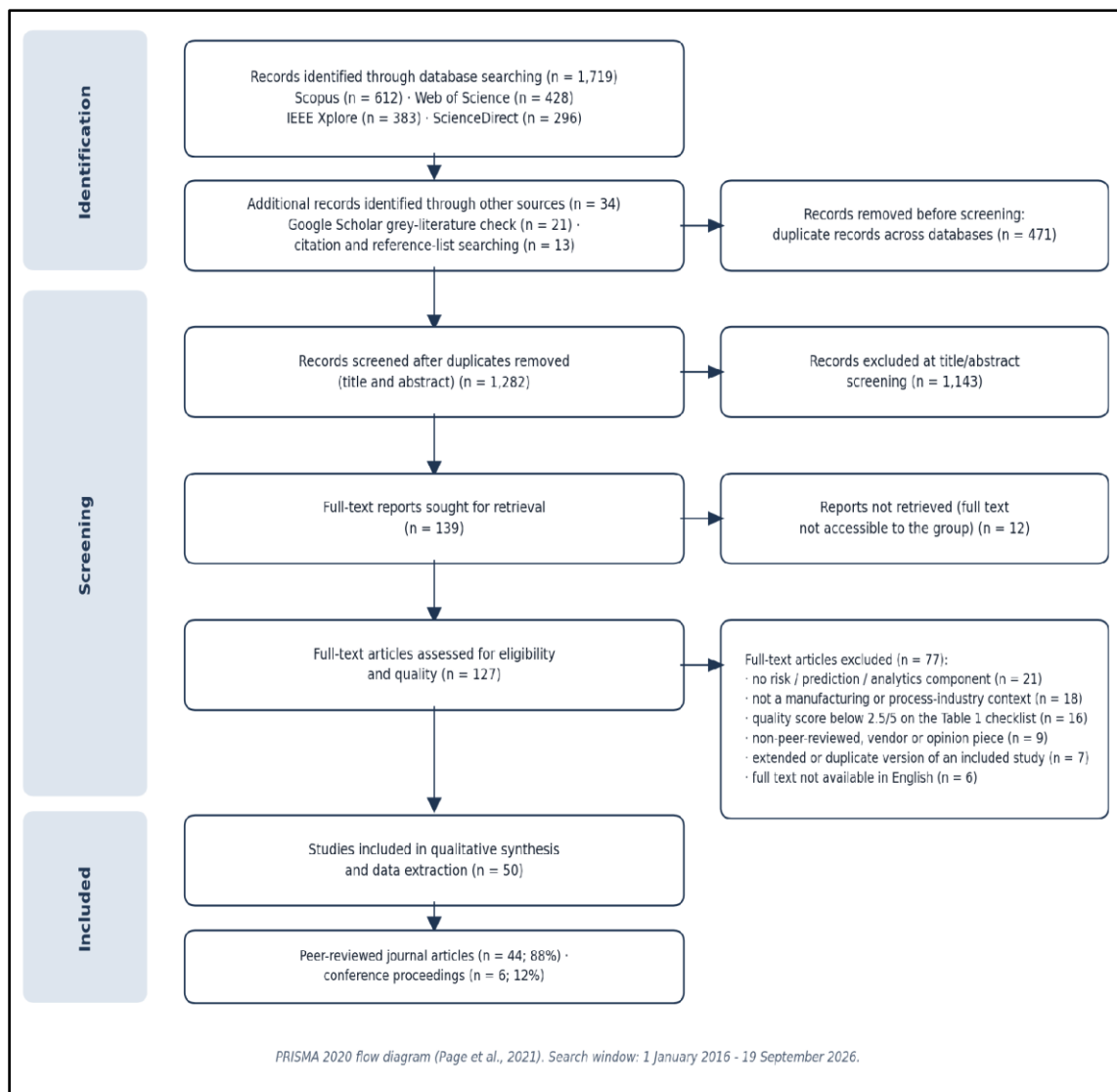


Figure 3: PRISMA 2020 flow diagram of the study identification, screening and inclusion process.

3.6 Data extraction, quality appraisal and synthesis

The authors, the publication date, the research objective, the manufacturing application, the data sources, the interoperability level, the exchange standard or framework, the system architecture, the technologies used, the reported benefits, the limitations and research gaps were extracted, consistent with the interoperability dimensions identified by Zeid et al. (2019), and recorded on a standardised extraction form for each of the studies.

All the studies included were evaluated with respect to their methodological clarity, relevance to the research questions, technical clarity and reporting of results and validation. Due to the variation of research designs, terminology, application domain and the approach used for its evaluation, a thematic synthesis was used (Braun and Clarke 2006; 2024). The findings were clustered according to data-exchange mechanism, level of interoperability, lifecycle integration, maturity of the Digital Twin, requirements for synchronisation, enabling technologies, barriers for implementation and validation maturity.

4 CLASSIFICATION AND TAXONOMY

A multidimensional classification framework was used to group the literature, with the aim of comparing the various data-exchange ways to enable the shift from static engineering models to dynamic Digital Twins. The taxonomy-development logic is based on Nickerson, Varshney and Muntermann (2013) and the Digital Twin maturity dimension is based on the model-shadow-twin distinction in Kritzinger et al. (2018). The eight dimensions are defined and examples are provided for each in Table 3.

Table 3: Taxonomy dimensions for classifying CAD-to-Digital Twin data-exchange frameworks.

Dimension	Definition	Examples
D1: Data-exchange mechanism	The principal method used to transfer or expose information.	STEP, IGES, AAS, OPC UA, MQTT, APIs.
D2: Interoperability level	The depth at which systems exchange and interpret information.	Geometric, syntactic, feature-level, semantic and organisational interoperability.
D3: Digital Twin maturity	The level of connection and interaction between the physical and digital entities.	Static CAD model, digital model, digital shadow and bi-directional Digital Twin.
D4: Lifecycle phase	The product or asset stage covered by the framework.	As-designed, as-manufactured, as-inspected and as-operated.
D5: Model fidelity	The degree of detail represented in the digital model.	Exact geometry, behavioural model, multiphysics model or reduced-order model.
D6: Synchronisation frequency	How frequently information is updated between systems.	Batch, periodic, near-real-time or low-latency control-loop updates.
D7: Interface architecture	The main interaction arrangement between systems and users.	Machine-to-machine, API-based, HMI, dashboard or augmented-reality interface.
D8: Digital/physical creation sequence	The relationship between the creation of the digital model and the physical asset.	Greenfield, brownfield or simultaneous development.

The dimensions together paint a picture of more than an isolated transformation from CAD to a dynamic Digital Twin, it's a journey involving multiple steps (from D1 to D6): from file-based to service-based exchange, from geometric to semantic interoperability, from digital model to bi-directional twin, from as-designed to as-operated, from batch to near-real-time synchronisation.

5 CRITICAL ANALYSIS AND SYNTHESIS

Simply moving from static CAD models to Dynamic Digital Twins is not just about transferring more data. It calls for a shift from geometry-based exchange to integrated architectures of information, which maintain context and meaning, identity and operation. A total of eight themes were derived from the synthesis (Tandi et al., 2025).

5.1 File-based and neutral-standard exchange

STEP and IGES are the most developed mechanisms on dimension D1 for the transfer of CAD geometry from one software to the other in a portable manner. They are ideal for the design stage transfer, including transfer from CAD to finite-element and CAD to CFD, as seen in the exoskeleton and wind-turbine studies in Section 2.3 (Tandi et al., 2025; Muyambo et al., 2025). However, with file exchange, each exchange is a snapshot, and it starts to deviate from the physical asset as soon as it becomes physically produced. It does not contain live operational data and frequently lacks feature history, parametric relationships and design intent upon translation to another format. The exchange of files thus locks in the as-designed condition, but is not sufficient to provide Digital Twin functionality (Petrenko, 2025; Sobociński et al., 2024).

5.2 Semantic interoperability

Semantic interoperability guarantees that data have the same meaning across various systems. Geometry, properties, asset information and operational data are connected through the help of ontologies, semantic models and Asset Administration Shells (Strohmeier et al., 2022). Maturity model approaches assume that most organisations operate on syntactic levels, that is, they can be parsed but may not be reliably interpreted by the receiving systems (Gebhard and Wang, 2026). In engineering processes, where the same parameter (e.g. a tolerance, a material grade, a sensor tag) can be named, scaled or structured differently in CAD, MES and maintenance systems, custom mapping must be created in each of the three systems (Liepert et al., 2026).

5.3 Industrial communication and real-time data

OPC UA and MQTT facilitate the exchange of sensor information, machine status, alarms and production data (Soni and Makwana, 2017; Velesaca et al., 2025). A multi-agent condition-monitoring framework for induction furnace equipment

in a copper cable manufacturer in Zimbabwe is presented to show the capability and limitations of this layer (Mashava et al., 2026). This data was passed to a JADE based agent platform via a Siemens S7-1200 PLC and an OPC server, with the data refreshed at 500ms, messages exchanged between agents within the platform were below 10ms, and all five fault scenarios were correctly detected on a hardware-in-the-loop testbed. The system realized the physical-to-digital data flow in a timely and automatic manner, thereby realizing the digital shadow on dimension D3. Each signal, however, was represented in a rule base and there was no connection to the design model of the furnace. Communication technologies are thus needed to be integrated with correct data modelling to maintain the meaning and link operational data to CAD-generated design data.

5.4 Lifecycle traceability and the digital thread

Engineering revisions, Manufacturing records, Inspection results and Maintenance events are linked by Digital threads and PLM systems. The primary issue they have is consistency of identifier, versions and change history across systems. A lesser talked about challenge is the knowledge acquired as part of the product, which relates design intent to realised part quality. This is the knowledge that is the result of design of experiments studies. In CNC Milling of mild steel, the dominant process factors quantified by Taguchi-based optimisation were feed rate (Mapindu et al., 2026), in plastic injection moulding, it was injection pressure and melt temperature (Mapindu et al., 2026a), and in fused deposition modelling, it was infill density (Mapindu et al., 2026b) and layer height (Mapindu et al., 2026c) for print time while in optimizing weld joint gas flow rate and current were key parameters (Mapindu et al., 2026d). Similar studies have correlated cutting parameters with surface quality and energy effectiveness in the machining of teak, saligna and pine (Tayisepi et al., 2023), and honing parameters with surface finish and energy consumption in engine-cylinder relining (Tayisepi et al., 2024). In process industries, predictive models obtained from experiments have been used to design a vacuum bleaching system for edible-oil refining (Jansen et al., 2025).

Generally, the validated process windows, signal-to-noise responses and regression models are stored in statistical software, project reports or offline and do not typically exist in PLM or CAM. A change of a CAD feature or material, embedded into the digital thread, that can be assessed, based on known process–quality–energy relationships, would further shift the process knowledge from the digital-model level towards a truly connected twin of the process.

5.5 Model fidelity versus computational efficiency

There may be a balance between the 'real' engineering information obtained from highly detailed models and the computational resources they consume, versus the suitability of simplified models for real-time use. This means that there is a compromise between the accuracy and processing cost (dimension D6) and update speed (dimension D5). One solution is to use reduced order (RO) and data-driven surrogates. Lightweight modelling methods like the orthogonal-array and grey relational models outlined in Section 5.4 can be assessed nearly instantaneously and predictive, model-based geometry adjustment has been shown to work for automotive body-in-white sub-assemblies (Schützenberger et al., 2024). A coal-fired power plant was used at the asset level to train a Random Forest (RF) classifier that was validated using the following operating weeks based on 13 years of monthly operating data to optimize boiler PM decisions (Senda et al., 2026). These models are based on data; they add to, but do not supplant, physics-based CAD and simulation models – the challenge is how to maintain consistency as the asset and the data evolves.

5.6 Brownfield integration and legacy equipment

Older manufacturing machines may not be equipped with the modern communication capability, which needs to be added, either using added sensors, gateways or retrofitted interfaces. This presents the need for adaptable architectures and phased implementation (dimension D8). Decisions based on evidence from Zimbabwe shows that outdated machines with no advanced safety features are still commonplace (Muhla et al., 2025), existing Industry 4.0 technologies are not interconnected (Muhla et al., 2025), and that maintenance at a major thermal power station was only 72% corrective (Senda et al., 2026), suggesting little use of condition data. The furnace case demonstrates the creation of a working digital shadow on a commodity-PLC in a brownfield furnace for relatively low investment (Mashava et al., 2026). The question for such an environment is not whether it is possible to achieve a full bi-directional twin, but what are the incremental steps that can be taken, and the ones that will get the most value up front by following standards.

5.7 Human factors, skills and interfaces

The ultimate goal of Digital Twins is to be used by people, and dimension D7 is a design variable that is explicitly related to the Digital Twin and how it is used by the people. The results of HWE studies indicate that, safety culture, ergonomic design and operator training greatly affect the results of the accidents in manufacturing (Muhla et al., 2025b). The twin dashboards, alarms and decision support outputs must therefore be designed not just with respect to the data available, but with respect to the operators' cognition. The human-centred design approach also applies to product. Assistive products whose performance will depend on the user have been proposed, such as a passive upper-limb exoskeleton with user-specific torque adjustment (Tandi et al., 2025) and a dual-mode smart wheelchair equipped with voice

control, joystick control and ultrasonic obstacle detection (Munotyaaani et al., 2026); the design models of these products could be adapted to become twin products for condition monitoring and personalisation in the above two instances, by adding the appropriate sensors. The need to have a workforce that can work across CAD, automation, data and analytics, and learning factories has been suggested as a regional approach towards developing such competences in the Southern African region (Ndiyamba et al., 2026).

5.8 Validation and cybersecurity

Digital Twins should be tested with explicit criteria like data accuracy, synchronisation delay, fault detection performance, and usefulness for decision making. Only a few studies in the literature are found that report such metrics on a regular basis and even fewer validate their frameworks in operational environments instead of in a laboratory. Where latency or accuracy of detection are reported for cases such as furnace or boiler, as described above, there is a template that can be followed (Mashava et al., 2026; Senda et al., 2026). Authentication, access control and network segmentation are also critical components of cybersecurity, as the introduction of engineering systems containing the design IP into plant-floor networks increases the potential attack surface of both systems.

5.9 A layered reference architecture

The themes above point towards a layered architecture in which each layer contributes a distinct type of information and relies on distinct exchange mechanisms. Table 4 summarises the proposed architecture and maps it to the taxonomy dimensions and illustrative evidence.

Table 4: Proposed layered reference architecture for CAD-to-Digital Twin data exchange.

Layer	Primary role	Typical exchange mechanisms	Taxonomy dimensions	Illustrative evidence
L1 Design intent	Authoritative geometry, tolerances, materials, configuration and revisions.	CAD/PLM; STEP and other neutral formats.	D1, D4 (as-designed), D5	Tandi et al. (2025); Muyambo et al. (2025); Sobociński et al. (2024)
L2 Semantic interoperability	Shared meaning, asset identity and context across systems.	Ontologies; AAS submodels; OPC UA information models.	D2	Strohmeier et al. (2022); Gebhard and Wang (2026); Liepert et al. (2026)
L3 Operational data	Time-stamped machine, process, quality and maintenance data.	PLC/SCADA/MES; OPC UA; MQTT; retrofitted sensors and gateways.	D4 (as-operated), D6, D8	Velesaca et al. (2025); Mashava et al. (2026); Senda et al. (2026)
L4 Twin services	Monitoring, simulation, prediction and optimisation.	Physics-based and data-driven models; APIs; agent platforms.	D3, D5	Schützenberger et al. (2024); Mapindu et al. (2026a; 2026b; 2026c)
L5 Human decision interface	Presentation, alerting and decision support for engineers and operators.	Dashboards; HMI; notifications; AR interfaces.	D7	Muhla et al. (2025b); Ndiyamba et al. (2026)

The architecture is deliberately technology-neutral. Its central claim is that the value of a Digital Twin depends on the integrity of L2: without a semantic layer that preserves identity and meaning, L1 and L3 remain disconnected data stores, and L4 services must rely on fragile, hand-built mappings.

6 RESEARCH GAPS AND FUTURE DIRECTIONS

In response to RQ4, the review identifies six principal gaps.

- **Gap 1: Design intent is lost at the CAD-operations boundary.** Current frameworks transfer geometry reliably but rarely carry parametric history, tolerancing rationale or feature semantics into operational systems. Future work should examine how neutral product models and AAS submodels can jointly carry design intent into the twin.

- **Gap 2: Process knowledge is not connected to the digital thread.** Experimentally validated process–quality–energy models, of the kind produced by design-of-experiments studies in machining, moulding, additive manufacturing and process industries (Tayisepi et al., 2023; 2024; Jansen et al., 2025; Mapindu et al., 2026), are seldom linked to CAD, CAM or PLM. Research is needed on representing such models as reusable twin services.
- **Gap 3: Brownfield and resource-constrained contexts are under-represented.** Most reported frameworks assume greenfield infrastructure and substantial investment. Low-cost, retrofit-based and phased architectures, such as PLC- and OPC-based digital shadows (Mashava et al., 2026), deserve systematic evaluation in developing industrial economies, where interconnectivity rather than technology availability is often the binding constraint (Muhla et al., 2025a).
- **Gap 4: Industrial validation and performance metrics are inconsistent.** There is no widely adopted set of metrics for twin fidelity, synchronisation latency, data quality or decision value. Common benchmarks and longer-term field validation are required.
- **Gap 5: Human, organisational and skills dimensions are neglected.** The literature concentrates on technical interoperability. Organisational interoperability, operator-centred interface design (Muhla et al., 2025b) and the workforce competences needed to build and use twins (Ndiyamba et al., 2026) warrant dedicated study, including the use of learning factories as twin testbeds.
- **Gap 6: Security and sustainability are treated as secondary concerns.** Few frameworks integrate cybersecurity by design, and few use the twin to track energy performance, even though machining energy is strongly parameter-dependent (Tayisepi et al., 2023; 2024) and renewable, decentralised energy assets are emerging as twin candidates in their own right (Muyambo et al., 2025).

7 CONCLUSION

The data exchange frameworks for a transition from static CAD to dynamic DT in Industry 4.0 manufacturing were studied and analyzed in this review. To answer RQ1, the literature has multiple approaches, such as neutral product-model standards, APIs, industrial communication protocols, semantic models, Asset Administration Shells, PLM and digital-thread architectures, with none of these alone being enough. As a response to RQ2, the following problems have been identified: loss of design intent, semantic heterogeneity, inconsistent identifiers, inconsistent versions and legacy equipment and a limited validation. With regard to RQ3, current standards and protocols are good enough for technical and syntactic interoperability, but not for semantic and organisational interoperability. As a response to RQ4, the review highlights the following gaps: Design intent, process knowledge, brownfield contexts, validation metrics, human and skills factors, and security and sustainability.

The study concludes that a layered and integrated approach is needed to get from static CAD models to dynamic Digital Twins, which should include CAD and PLM data, neutral standards, semantic models and industrial communication protocols and lifecycle traceability. Moving forward, secure semantic interoperability, low-cost brownfield integration, incorporation of validated process knowledge into the digital thread, measurable industrial validation, and balancing between model fidelity and real-time performance are priorities to be addressed in future research. The journey to the Digital Twin will likely be an incremental one for developing industrial economies – starting from well designed digital shadows and the skills needed to maintain them.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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There is no conflict of interest.

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