



CLOUD-BASED CAD/CAM COLLABORATION PLATFORMS FOR DISTRIBUTED MANUFACTURING: A SYSTEMATIC REVIEW

Anesu Cephas Chawira *, Alex J. Dube, Luckson Chakandinakira and Kennedy Sungai

Department of Industrial and Manufacturing Engineering, Faculty of Engineering, National University of Science and Technology (NUST), P.O. Box AC 939, Ascot, Bulawayo, Zimbabwe.

* Corresponding Author

Open Access Research Journal of Science and Technology, 2026, 18(01), 111–125

Publication history: Received on 26 August 2026; revised on 01 October 2026; accepted on 03 October 2026

Article DOI: <https://doi.org/10.53022/oarjst.2026.18.1.0094>

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

Engineering practices are changing from file-centric desktop models to multi-user, real-time, cloud-based computer-aided design and manufacturing (CAD/CAM) platforms like Onshape, Autodesk Fusion, 3DEXPERIENCE and Siemens NX X that serve as a complement to cloud manufacturing (CMfg) and Industry 4.0. This paper summarizes the capabilities and limitations of distributed manufacturing and cloud-based CAD/CAM, the drivers for the adoption of cloud-based CAD/CAM, and the integration architectures. In line with the PRISMA 2020 guidelines, 312 records were identified from IEEE Xplore, Scopus, Web of Science and ScienceDirect databases and were then synthesized thematically to a total of 87 (87%) primary studies published between January 2016 and 06/26/2026. The review suggests a four-dimensional taxonomy of platforms based on: architectural model, granularity of collaboration, depth of manufacturing integration and adherence to a standard for interoperability. In looking at the taxonomy, there is a constant riddle of how platforms with a fine-grained real-time co-editing feature deliver shallow manufacturing integration, while the PLM-based platforms offering deep MES/ERP and digital-twin integration maintain coarse check-out-based co-editing. Empirical studies demonstrate the benefits of simultaneous access in the form of new modes of teamwork, but that benefits in terms of quality and productivity rely on design of work processes and team dynamics and permissioning. The major challenges to adoption are not platform maturity, but the absence of standards for exchanging parametric models and integrating CAD with MES, inadequate evidence of IP-protection and a lack of evidence from the developing world where connectivity, power reliability and skills are very different. The paper identifies eight priority research directions based on the process-optimisation, condition monitoring and Industry 4.0 adoption studies conducted in Zimbabwe and discusses implications for practitioners and for engineering education using learning factories.

Keywords: cloud-based CAD; Cloud Manufacturing; Collaborative Design; Distributed Manufacturing; Digital Twin; Interoperability; Industry 4.0; PLM; Developing Economies; Systematic Review

1 INTRODUCTION

The existing desktop computer-aided design and manufacturing (CAD/CAM) software was designed within a local (organisational and geographical) scope, which has led to lasting demand for the engineering design tools to operate beyond the traditional limits of the desktop workspace in the digital transformation of manufacturing (Lasi et al., 2014; Zhong et al., 2017; Xu, Xu and Li, 2018). The late 1980s and early 2000s era of an engineer using a locally installed parametric modeller and regularly syncing files to an on-premises product data management (PDM) system is not

necessarily reflecting the operating environment of distributed manufacturing. Design teams are spread out and need to access product data concurrently, supply chain partners must have access to product data concurrently, and time-to-market pressures call for parallel engineering processes instead of sequential (Stark, 2015).

To overcome this misalignment, cloud-based, browser-based CAD/CAM systems, such as Onshape, Autodesk Fusion, 3DEXPERIENCE platform (Dassault Systèmes) and Siemens NX X/Teamcenter X, have moved geometric modelling, data management and, in increasing numbers, simulation and toolpath generation to shared cloud infrastructure (Wu et al., 2015). From the architectural point of view, these platforms are based on the cloud manufacturing (CMfg) paradigm, which virtualises manufacturing resources and capabilities to provide on-demand services (Li et al., 2010; Tao et al., 2011; Xu, 2012). The advantages for practice are significant: no file versioning problems, multi-user editing, reduced entry barriers for small and medium enterprises (SMEs) and a single authoritative product model to feed downstream manufacturing systems.

The pledge is especially significant for manufacturers of developing world countries. In the context of Zimbabwean factories, the findings of the surveys indicate a disorganized approach to the use of Industry 4.0 technologies, with key constraints highlighted as the lack of a digital strategy and the high costs of solutions as well as limited government support (Muhla et al., 2025b). The authors also discovered that companies looking to be agile see the technology of integrating production with design and the fast flow of customer feedback into product development as prerequisites to competing with imported products (Muhla et al., 2023). Cloud-based CAD/CAM, in the form of subscription model, directly tackles the capital-cost barrier, but also brings in new dependencies on connectivity, data governance and skills, which have yet to be systematically addressed in the literature. Previous reviews have outlined collaborative CAD architectures (Fuh and Li, 2005; Li et al., 2005); proposed research agendas for multi-user computer aided applications (Red et al., 2010); and viewed cloud-based design and manufacturing as a new paradigm (Wu et al., 2015). The service composition, scheduling and business models have been broadly discussed in the context of cloud manufacturing (He and Xu, 2015; Adamson et al., 2017).

A systematic link between the potentially undeniably growing commercial cloud CAD/CAM platforms, however, to (i) empirical evidence of collaborative design performance, (ii) level of integration with downstream manufacturing systems and (iii) specific constraints of distributed manufacturing in resource-constrained environments has not been made. This paper attempts to fill that gap. The review aims at: (1) characterising the technological characteristics of cloud based CAD/CAM collaboration platforms, including the architectural models, functional aspects and positioning of such platforms in the market; (2) synthesising the empirical and theoretical literature on the use of such platforms in distributed manufacturing environments; (3) developing a taxonomy that classifies the existing platforms and literature into a coherent analytical framework; (4) identifying key limitations, open challenges and research gaps; and (5) suggesting a structured research agenda.

The review has three contributions. For one, it suggests a taxonomy of four dimensions (architecture, granularity of collaboration, depth of manufacturing integration and interoperability) by which it is possible to compare platforms and studies on a common basis. Second, it critically aggregates the evidence and differentiates between real-world effects and vendor claims and conceptual proposals. Thirdly, it identifies eight research directions and even spells out an agenda for the manufacturing contexts of developing economies, which is very little represented in the existing body of literature.

2 BACKGROUND AND THEORETICAL FOUNDATION

2.1 The evolution from desktop to cloud-native CAD/CAM

The evolution of commercial CAD has been one of gradual enrichment of the accurate and sophisticated capability of geometric modelling: beginning with 2-D drafting systems in the early 1980s, then parametric solid modelling introduced in 1988 by Pro/ENGINEER, and finally feature-based history-driven parametric modellers that are now used by the majority of serious engineering practitioners (Whitney, 2004).

The PDM systems were added from the late 1980s onwards, which gave version controlled vaults where CAD files were checked in and out and prevented concurrent editing. Product lifecycle management (PLM) then extended this capability to the entire engineering data that is used to create a product and retire it in the future (Grieves, 2006; Stark, 2015). The potential of client-server and peer-to-peer architectures for distributed, collaborative CAD for sharing geometry between designers emerged in the 2000s but were mostly limited to research prototypes due to the computational and bandwidth limitations of the era (Fuh and Li, 2005; Li et al., 2005). Many of these constraints were eliminated with the maturation of cloud computing, which is characterized by on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service (Mell and Grance, 2011).

The authoritative model is now in the cloud as a database of features and operations, where concurrent edits can be merged at the operation level. This is a change in how this type of operation is handled, principles developed for real-time groupware (Ellis and Gibbs, 1989) and forms the base of the collaboration granularity dimension of the taxonomy presented in Section 4. The change is also important for the design/analysis loop. Traditionally, ideas for concepts are created in one package and sent to another package for finite element analysis (FEA), as three concepts for a passive upper-limb exoskeleton were created in SolidWorks and tested in ANSYS for deformation, stress and factor of safety, and then the device weight was reduced to 2.6 kg through topology optimisation (Tandi et al., 2025). In the case of a vertical axis wind turbine (VAWT) that is to be used for energy harvesting from the wind slipstream, similar CAD-to-computational fluid dynamics (CFD) iterations were necessary before prototyping could be performed (Muyambo et al., 2025). In this review, simulation integration is considered a standalone level of manufacturing integration depth as it enables cloud platforms that co-locate geometry, simulation and data.

2.2 Cloud manufacturing (CMfg) as a theoretical framework

The CMfg model is based on manufacturing capabilities such as design, simulation, process planning, production, testing and management as virtualised services that can be discovered, composed and invoked on demand by geographically distributed users through a cloud platform, which are conceptualised as virtualised manufacturing capabilities (Li et al., 2010; Tao et al., 2011; Xu, 2012). Further research has identified the necessary attributes of CMfg: service orientation, resource virtualisation, on-demand provisioning and collaborative value creation, and has recorded several pilot applications (Ren et al., 2015; Ren et al., 2017). However, critical reviews point out that work is still far from the conceptual literature in terms of interoperability, security and maturity of the business model (He and Xu, 2015; Adamson et al., 2017).

In the CMfg context, CAD/CAM platforms that include cloud-based capabilities are the implementation of design and manufacturing-planning capabilities as cloud services. In theory, this means that they are the base layer in a CMfg ecosystem; services to support virtual manufacturing, simulation, process planning and CNC toolpath generation are built upon them (Wu et al., 2015). The demonstration of a cloud-based adaptive process planning, which considers the actual availability and capability of the machine tool, allows the creation of such a design layer that can be coupled to the shop floor resources (Mourtzis et al., 2016). These relationships are combined in Figure 3 (Section 5.5) in the form of a digital-thread framework.

2.3 Process knowledge as a service: the CAM side of the digital thread

A cloud CAD model is a manufacturing asset when it's associated with validated process knowledge. In reality, a large amount of that knowledge is acquired during the design of experiments (DOE) process, and not through first-principles models. The wide range of knowledge about the process parameters that could be captured and reused, in principle, by a cloud CAM environment is demonstrated by the taguchi-based studies conducted in the authors' research group. The study resulted in the conflict of the optimum values for surface roughness and spindle speed being resolved to a single optimum value for mild steel CNC milling, using grey relational analysis (GRA), with 82.81% of the variation in surface roughness accounted for by the feed rate and 63.40% of the variation in flank tool wear accounted for by the spindle speed (Mapindu et al., 2026c). Again, for fused deposition modelling (FDM), infill density was the most important parameter for tensile strength, whereas layer height was the most important parameter for print time, which needed a multi-response compromise (Mapindu et al., 2026b). The injection pressure and the melt temperature accounted for approximately 90% of the variance in shrinkage and warpage in injection moulding (Mapindu et al., 2026a). Current and arc voltage were determined to be the most significant factors in optimizing weld strength, responsible for the variance in tensile strength (Mapindu et al., 2026d).

The knowledge of energy-aware process also is relevant. Honing of cast-iron cylinder relining sleeves revealed that optimum parameters varied with the objective of the honing process, either maintaining surface roughness or power or total energy (Tayisepi et al., 2024). Comparative machining of teak, saligna and pine showed that optimum cutting parameters were material-dependent (Tayisepi et al., 2023). The same experimental design strategy is transferred to the other types of manufacturing; in the case of the vacuum bleaching of edible oil, an L12 orthogonal array was used to model the colour and free fatty acid response, from which regression models were derived, and these models were used to design the bleaching system computationally via CAD (Jansen et al., 2025). All these studies indicate that the best parameters are specific to the machine, material and context used. This further underscores the importance of parameter libraries as a versioned, shareable and contextualized service, not as a static default.

3 REVIEW METHODOLOGY

3.1 Review protocol

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page *et al.*, 2021), complemented by established guidance for systematic reviews in engineering and management research (Tranfield, Denyer and Smart, 2003; Kitchenham and Charters, 2007). The protocol specified the research questions, search strings, databases, eligibility criteria, screening procedure, data-extraction template and synthesis method before screening began.

3.2 Research questions

Five primary research questions (PRQs) guided the review:

- PRQ1: What are the principal architectural models and functional capabilities of cloud-based CAD/CAM collaboration platforms described in the academic literature?
- PRQ2: What empirical evidence exists for the effectiveness of these platforms in supporting real-time collaborative design in distributed manufacturing environments?
- PRQ3: How are cloud-native CAD/CAM platforms integrated with downstream manufacturing systems, including CAM, simulation, manufacturing execution systems (MES) and enterprise resource planning (ERP)?
- PRQ4: What technical, organisational and human-factors limitations and challenges are reported?
- PRQ5: What research gaps and future directions are identified by existing studies?

3.3 Search strategy and database selection

Searches were conducted in four databases: IEEE Xplore, Scopus, Web of Science Core Collection (SCI-EXPANDED and CPCI-S) and ScienceDirect. These were selected for their coverage of engineering, computer science and manufacturing systems literature and for their complementary indexing of conference proceedings alongside journal articles. The search string combined three concept blocks (Table 1). Secondary searches used platform-specific terms (Onshape, Fusion 360, 3DEXPERIENCE, Siemens NX Cloud, Teamcenter X, PTC Creo+, Trimble Connect) to capture evaluation studies that refer to commercial product names. Backward and forward citation searching (snowballing) of the included studies was used to check completeness (Wohlin, 2014).

Table 1: Search string structure (title, abstract and keyword fields)

Concept block	Search terms (combined with OR within block; blocks combined with AND)
A. Technology	"cloud-based CAD" OR "cloud CAD" OR "web-based CAD" OR "browser-based CAD" OR "multi-user CAD" OR "collaborative CAD" OR "cloud CAM" OR "cloud PLM" OR "CAD as a service"
B. Collaboration	collaborat* OR concurren* OR "real-time" OR "co-design" OR "distributed design" OR "multi-site"
C. Manufacturing context	manufactur* OR "product development" OR "cloud manufacturing" OR "Industry 4.0" OR "smart manufacturing" OR "digital twin"
Limits	Publication years 2016–2026 (to June); English language; journal articles, conference papers and book chapters

3.4 Eligibility criteria

Inclusion criteria: (1) peer-reviewed journal articles, conference papers or book chapters; (2) published between January 2016 and June 2026; (3) written in English; (4) addressing cloud-based or network-delivered CAD, CAM or PLM systems in a manufacturing or engineering design context; and (5) empirical, theoretical or review studies with a clear methodological basis.

Exclusion criteria: (1) publications before January 2016, to maintain currency and exclude literature from before the cloud-native platform era; (2) commercial white papers, vendor documentation or marketing materials without peer review; (3) studies addressing cloud computing in manufacturing but not design-tool collaboration; (4) duplicate publications, retaining only one record per study; and (5) studies of cloud-based simulation or FEA tools without a connection to CAD/CAM collaboration.

3.5 Study selection

Two reviewers independently screened titles and abstracts against the eligibility criteria, and disagreements were resolved by discussion with a third reviewer. The database searches identified 312 records: IEEE Xplore ($n = 84$), Scopus ($n = 97$), Web of Science ($n = 74$) and ScienceDirect ($n = 57$). After removal of 65 duplicates, 247 unique records were screened on title and abstract, and 118 were excluded. Full texts of the remaining 129 reports were assessed, and a further 42 were excluded because they did not specifically address CAD/CAM collaboration ($n = 18$), were published before January 2016 ($n = 7$), were not peer-reviewed ($n = 9$) or lacked a sufficient methodological basis ($n = 8$). The final corpus comprised 87 primary studies (Figure 1).

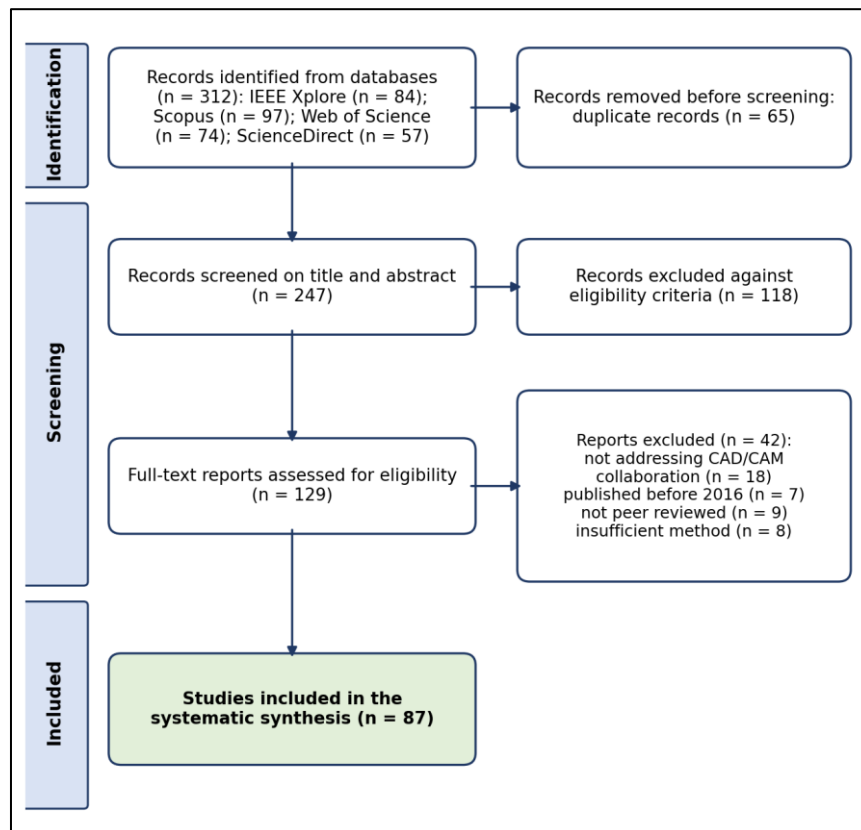


Figure 1: PRISMA 2020 flow diagram of study identification, screening and inclusion. Source: authors' own elaboration, adapted from the PRISMA 2020 flow diagram template (Page *et al.*, 2021).

3.6 Data extraction, quality appraisal and synthesis

A structured extraction form captured bibliographic data, study type (empirical, design-science, conceptual or review), platform(s) studied, architectural model, collaboration mechanism, manufacturing integration reported, interoperability standards referenced, sample and setting, outcome measures and reported limitations. Methodological quality was appraised using a five-item checklist covering clarity of aims, appropriateness of design, transparency of data, validity of conclusions and acknowledgement of limitations. Because the corpus is heterogeneous and few studies report comparable quantitative outcomes, a meta-analysis was not appropriate. The findings were therefore integrated through thematic synthesis (Thomas and Harden, 2008): studies were coded line by line, descriptive themes were developed inductively, and analytical themes were mapped onto the research questions. The four taxonomic dimensions presented in Section 4 emerged from this analytical stage.

Studies from the authors' research group on process optimisation, condition monitoring, maintenance, human factors and Industry 4.0 adoption in Zimbabwe (Section 2.3 and Section 5) fall outside the search scope because they do not address cloud CAD/CAM directly. They were therefore not counted in the synthesis corpus. They are used as contextual evidence to interpret the findings for resource-constrained manufacturing settings.

3.7 Threats to validity

Four threats are acknowledged. First, restricting the search to English-language, peer-reviewed sources may under-represent practitioner knowledge and non-English literature, notably from China, where CMfg research is extensive. Second, the rapid evolution of commercial platforms means that some technical characterisations date quickly; the platform assessment in Table 3 reflects publicly documented capabilities as of mid-2026. Third, keyword searches may

miss studies that describe cloud CAD functionality under other terms; snowballing was used to mitigate this. Fourth, the classification of studies into taxonomic levels involves reviewer judgement; this was mitigated through dual coding and consensus discussion.

4 CLASSIFICATION AND TAXONOMY

4.1 Taxonomy development

Analysis of the 87 included studies showed that cloud-based CAD/CAM platforms, and the research concerning them, can be organised along four largely independent dimensions (Figure 2): (D1) architectural model, describing how computation and storage are allocated between server and client; (D2) collaboration granularity, describing the finest unit of design work that multiple users can access concurrently; (D3) manufacturing integration depth, describing the extent of connection to downstream manufacturing systems; and (D4) interoperability standard adherence, describing support for neutral data exchange.

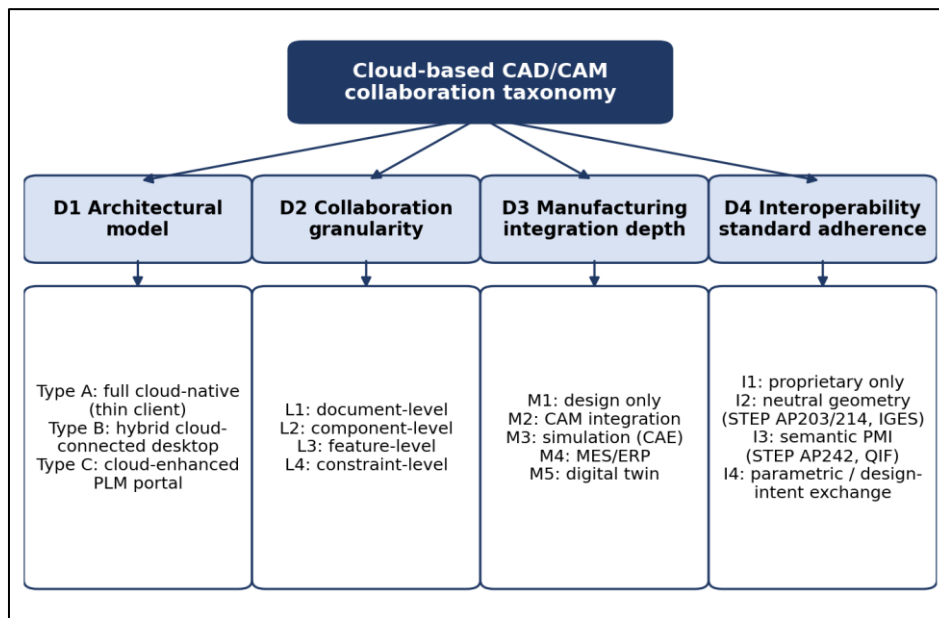


Figure 2: Four-dimensional taxonomy of cloud-based CAD/CAM collaboration platforms. Source: authors' own elaboration.

4.2 Dimension 1: Architectural model

Three architectural models were identified. Type A (full cloud-native, thin client) platforms execute geometric modelling kernels, data management and rendering on the server, delivering the interface through a web browser or lightweight application; the model exists only as a server-side database, and there are no local files. Type B (hybrid cloud-connected desktop) platforms retain a locally installed modelling client but synchronise the model and its history with cloud storage, offloading selected compute-intensive services, such as generative design, simulation and rendering, to the cloud. Type C (cloud-enhanced PLM portal) platforms extend established PLM backbones to the cloud. They provide cloud-hosted data management, workflow and visualisation around desktop authoring tools, and prioritise enterprise-wide governance over real-time co-editing.

4.3 Dimension 2: Collaboration granularity

Collaboration granularity is the finest unit of design work that multiple users can access concurrently without serialisation. Four levels are distinguished:

- Level 1, document level: users may work on different documents (parts or assemblies) in a project at the same time, but access to any single document is serialised by check-out.
- Level 2, component level: users may simultaneously edit different components of the same assembly, but edits to the same component are serialised.
- Level 3, feature level: users may simultaneously edit different features of the same part model, with server-mediated conflict resolution when edits interact.

- Level 4, constraint level: users may simultaneously add, modify and delete individual constraints and parameters in the same sketch or assembly constraint set, with real-time resolution of constraint conflicts.

4.4 Dimension 3: Manufacturing integration depth

Five levels of manufacturing integration were identified:

- M1, design only: the platform manages geometric design data without integration with process planning, simulation or execution.
- M2, CAM integration: the platform includes, or is directly connected to, cloud-delivered toolpath generation, enabling CNC programs to be produced directly from the cloud-hosted model.
- M3, simulation integration: the platform is connected to FEA, CFD or manufacturing-process simulation services, enabling design validation within the cloud environment.
- M4, MES/ERP integration: the platform exchanges data with MES and ERP systems, enabling automatic generation of manufacturing bills of materials, work instructions and production schedules.
- M5, digital twin integration: the platform is bidirectionally connected to a digital twin infrastructure, so that production and operational data can update or validate the design model (Kritzinger *et al.*, 2018; Tao *et al.*, 2019b).

4.5 Dimension 4: Interoperability standard adherence

Interoperability, meaning the ability to exchange design and manufacturing data between platforms without loss of semantic fidelity, is one of the most persistent and practically significant challenges for cloud CAD/CAM in distributed manufacturing (Wang and Xu, 2013). Four levels are distinguished: I1, proprietary formats only; I2, neutral exchange of boundary-representation geometry (for example STEP AP203/AP214 or IGES); I3, semantic exchange of product and manufacturing information (PMI), such as geometric dimensioning and tolerancing, through STEP AP242 or QIF; and I4, exchange of parametric, history-based models with preserved design intent. Level I4 has been demonstrated in research settings (Kim *et al.*, 2008) but is not yet supported in practice by commercial platforms.

Table 2: Summary of taxonomy dimensions, levels and primary research questions addressed

Dimension	Levels	Principal question for users	Related PRQ
D1 Architectural model	Type A, B, C	Where do computation and the authoritative model reside?	PRQ1
D2 Collaboration granularity	L1–L4	How finely can concurrent work be divided?	PRQ1, PRQ2
D3 Manufacturing integration depth	M1–M5	How far downstream does the model travel without re-entry?	PRQ3
D4 Interoperability adherence	I1–I4	What is lost when data leave the platform?	PRQ3, PRQ4

4.6 Comparative assessment of principal platforms

Table 3 applies the taxonomy to the principal platforms discussed in the reviewed studies. The classification reflects the authors' assessment of publicly documented platform capabilities and of how the platforms are characterised in the included studies. It is not a vendor benchmark.

Table 3: Comparative assessment of principal cloud-based CAD/CAM platforms

Platform	D1 Architecture	D2 Granularity	D3 Integration	Key distinguishing characteristics
Onshape (PTC)	Type A	Level 3	M2–M3	Database-backed parametric modeller; version graph replaces file saves; branching and merging; partner app ecosystem
Autodesk Fusion	Type B	Level 2	M2–M3	Integrated CAD/CAM/CAE/electronics; generative design; strong SME and education adoption

3DEXPERIENCE (Dassault Systèmes)		Type C	Level 1–2	M3–M5	Full PLM scope; ENOVIA-based change management; virtual twin and manufacturing apps
Teamcenter (Siemens)	X	Type C	Level 1	M4–M5	Deep MES/ERP integration; NX and Solid Edge authoring; automotive and aerospace use
PTC Creo+		Type B	Level 2	M3–M4	Windchill cloud integration; augmented reality via Vuforia; IoT via ThingWorx
Trimble Connect		Type C	Level 1–2	M1–M2	Construction/AEC focus; BIM and IFC support; multi-user model review

Note: classification reflects publicly available platform documentation as of mid-2026 and the characterisation of platforms in the included studies.

A clear pattern emerges. Platforms with the finest collaboration granularity (Type A, Level 3) tend to offer shallower manufacturing integration, whereas platforms with the deepest manufacturing integration (Type C, M4–M5) offer coarser, check-out-based collaboration. This granularity–integration trade-off reflects different design lineages: Type A platforms were built around real-time co-editing, while Type C platforms evolved from PLM systems built around governance and change control. Resolving the trade-off is a central architectural challenge (Section 6).

5 CRITICAL SYNTHESIS AND DISCUSSION

5.1 Collaboration effectiveness: what the evidence shows

Empirical evidence on multi-user CAD performance has grown but remains concentrated in controlled, often student-based, experiments. In an early competition-style study in which teams modelled parts using a multi-user CAD prototype, team-member dynamics, such as how the modelling work was divided and coordinated, strongly influenced team performance (Stone *et al.*, 2017). A controlled experiment with 60 participants on a cloud-native platform found that pairs working with a single shared input produced higher-quality models than individuals, while pairs working in parallel on two inputs did not. Individuals remained faster per person (Phadnis *et al.*, 2021). The authors conclude that work-process choices influence design outcomes as much as tool capability does.

Evidence from practice points to a gap between capability and use. An interview study of 20 CAD professionals across industries identified 14 challenges related to collaborative design, communication, data management and permissioning, concluding that the CAD ecosystem lags behind collaboration practices in other knowledge-work domains (Cheng *et al.*, 2023). In education, a multi-user CAD collaborative learning framework has been proposed to structure how students learn to share and divide modelling work (Deng *et al.*, 2022). Across the corpus, three conclusions are warranted: (i) simultaneous access alone does not guarantee productivity gains; (ii) outcomes depend on task decomposition, communication and role clarity; and (iii) there is little longitudinal evidence from industrial deployments. The literature does not yet support quantitative claims about time savings in industrial practice.

Distributed collaboration in the authors' own context shows why these findings matter. The development of a dual-mode smart wheelchair for users in Zimbabwe involved engineers at institutions in Indonesia and Zimbabwe working on frame design, motor sizing and control integration (Munotyaani *et al.*, 2026). Projects of this kind, involving cross-border teams, constrained budgets and iterative hardware-software integration, are precisely where shared, versioned product models and clear permissioning could reduce coordination overhead, and they provide natural settings for future field studies.

5.2 The granularity–integration trade-off

The trade-off identified in Section 4.6 has practical consequences. Engineering teams that prioritise concurrent concept development benefit most from Type A platforms, while organisations whose priority is controlled release to manufacturing, with traceable engineering change, benefit from Type C platforms. Many firms therefore operate hybrid toolchains, authoring in one environment and releasing through another. This reintroduces the very file-transfer boundaries that cloud-native design was intended to remove, and it places interoperability (Section 5.3) on the critical path. Research on how to combine operation-level concurrency with PLM-grade change governance is sparse and is identified as a priority.

5.3 Interoperability and data exchange

Interoperability between cloud CAD/CAM platforms and the heterogeneous ecosystem of CAE, CAM, MES, ERP and legacy CAD tools is consistently identified as one of the most significant adoption barriers (Wang and Xu, 2013; Adamson

et al., 2017). Neutral formats reliably transfer boundary-representation geometry, but the exchange of richer semantics is uneven. Conformance testing of PMI in STEP files exported from commercial CAD systems revealed frequent errors and omissions in the representation of tolerances and annotations, even where the standard supports them (Lipman and Lubell, 2015). The exchange of parametric, history-based models that preserve design intent has been specified and demonstrated in research (Kim *et al.*, 2008), yet it is not supported in routine practice. As a result, a model shared across platforms typically arrives as "dumb" geometry that must be re-parameterised. This loss is especially costly in distributed supply chains, where suppliers use different authoring systems.

5.4 Security, intellectual property and governance

Security and intellectual property (IP) concerns recur throughout the corpus as reasons for hesitation, particularly in defence, aerospace and highly competitive consumer sectors. Cloud manufacturing broadens the attack surface through multi-tenancy, third-party service composition and cross-border data flows, and it complicates forensic investigation after incidents (Esposito *et al.*, 2016). Technical approaches to protecting design IP during collaboration include sharing simplified skeleton models in place of full-detail geometry (Mun, Hwang and Han, 2009) and partial or parametric encryption of feature-based models, so that collaborators can view and use only authorised regions of a model (Cai *et al.*, 2015; Cai *et al.*, 2017). These techniques are promising, but they have been demonstrated mainly on laboratory models, and their computational overhead and usability at production scale remain insufficiently characterised.

5.5 Integration with manufacturing execution, condition monitoring and digital twins

The integration of cloud CAD/CAM with MES and digital-twin infrastructure is the frontier of research at the manufacturing-systems level, and it is the area where the gap between conceptual proposals and deployed systems is widest. Digital-twin frameworks position the design model as the geometric and physical foundation of a twin that is connected, through data-integration middleware, to simulation, process and as-built representations (Tao *et al.*, 2018; Qi and Tao, 2018; Tao *et al.*, 2019a). A categorical review of the digital-twin literature found that most reported "digital twins" are in fact digital models or digital shadows lacking automatic bidirectional data flow (Kritzinger *et al.*, 2018). The same pattern holds for cloud CAD: fully closed design–production feedback loops (level M5) remain rare in the corpus.

The data side of this loop is maturing faster than the design side. In a Zimbabwean copper-cable plant, a FIPA-compliant multi-agent system connected infrared, flow, conductivity and level sensors through a Siemens S7-1200 PLC and an OPC server to JADE agents. The system detected all injected fault classes on an induction furnace testbed, with no false positives during a 72-hour nominal run (Mashava *et al.*, 2026). At a coal-fired power station, a random-forest model trained on 13 years of operating data identified an optimum boiler reliability region and the associated maintenance-cost and availability outcomes (Senda *et al.*, 2026). Such condition-monitoring and machine-learning pipelines provide exactly the operational data that an M5-level design platform would need to close the loop, for example by feeding failure modes back into design reviews. What is missing is a standardised pathway from these shop-floor data streams to the product model. Figure 3 synthesises the layers involved.

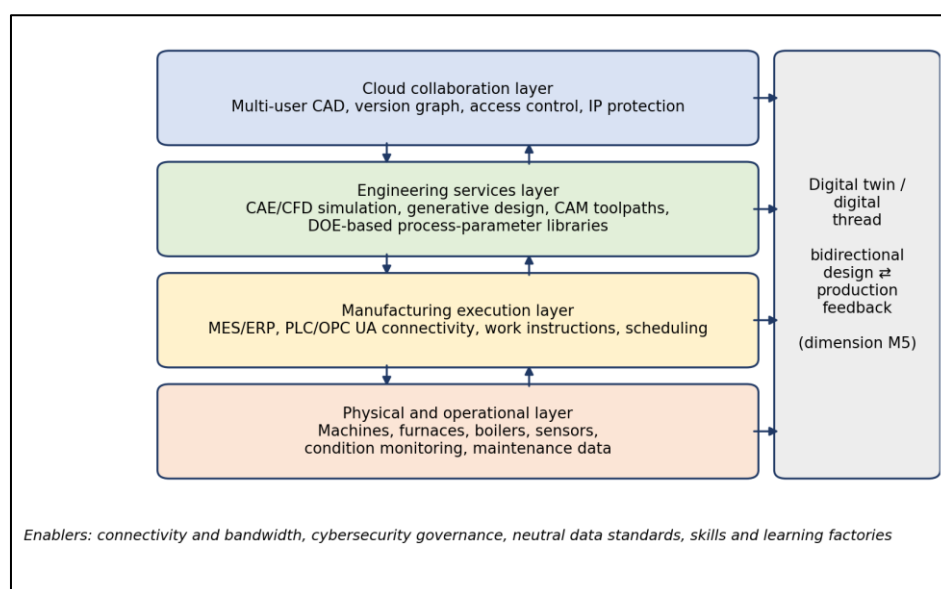


Figure 3: Layered digital-thread framework linking cloud CAD/CAM collaboration to manufacturing execution and operational data. Source: authors' own elaboration based on the synthesis.

5.6 Human factors and distributed design cognition

Collaborative design is a cognitive and social activity as well as a technical one. Shared mental models of the task, the team and the artefact are associated with more effective design collaboration (Badke-Schaub *et al.*, 2007). Integrating knowledge across disciplinary boundaries in new product development teams is complex, and misunderstandings frequently arise from differences in language, priorities and tacit knowledge (Kleinsmann, Buijs and Valkenburg, 2010). Cloud platforms make concurrent editing possible, but they do not by themselves communicate why a design decision was made. Several included studies report that design rationale and intent are poorly captured in shared models, which increases rework when downstream partners modify geometry without understanding the constraints behind it.

Human factors also extend to the manufacturing end of the digital thread. In Zimbabwean manufacturing, ergonomic design, operator training and safety culture have been shown to be significant in reducing workplace accidents (Muhla *et al.*, 2025a), and ergonomic considerations drove the design requirements of the exoskeleton discussed in Section 2.1 (Tandi *et al.*, 2025). Embedding ergonomic and safety knowledge in shared cloud models, for example as reusable design rules or annotated PMI, is an under-explored way to carry human-factors engineering from design into production.

5.7 Adoption in developing-economy manufacturing contexts

The overwhelming majority of empirical studies in the corpus are set in Europe, North America, China, Japan or South Korea. Evidence from Zimbabwe suggests that the conditions for adoption differ materially. Manufacturers already use computers, sensors, PLCs and the internet, but these are rarely interconnected or optimised, and firms cite the lack of an Industry 4.0 strategy, high costs, weak government incentives and fear of cyber-attack as barriers (Muhla *et al.*, 2025b). Agile manufacturing studies in the same context found that rapid-prototyping and numerically controlled equipment are in short supply, and they identified integration of design with production as a key enabler (Muhla *et al.*, 2023). Unreliable grid electricity, a constraint that also motivates renewable-energy research such as slipstream wind harvesting for EV charging (Muyambo *et al.*, 2025), adds a further risk for platforms that assume continuous connectivity.

These conditions cut both ways. Subscription pricing, browser access and free educational licences lower the entry barrier relative to perpetual desktop licences and on-premises PDM servers. However, bandwidth limits, latency, power interruptions, foreign-currency billing and data-sovereignty concerns may erode those advantages. No study in the corpus measured cloud CAD usability or productivity under the connectivity conditions typical of sub-Saharan African manufacturing, and this is one of the clearest gaps identified by the review.

6 RESEARCH GAPS AND FUTURE DIRECTIONS

6.1 Summary of identified research gaps

- Gap 1: Parametric model interoperability. No widely implemented standard supports the neutral exchange of parametric, history-based models between cloud-native platforms with preserved feature structure, design intent and manufacturing annotations. Research is needed to operationalise existing proposals (Kim *et al.*, 2008), extend STEP AP242 and define conformance tests of the kind developed for PMI (Lipman and Lubell, 2015).
- Gap 2: Scalable real-time collaboration for large teams. Controlled evidence comes predominantly from individuals, pairs and small teams (Stone *et al.*, 2017; Phadnis *et al.*, 2021). Research is needed on awareness mechanisms, task decomposition and conflict-resolution protocols that sustain effectiveness for the larger, multi-organisation teams typical of complex manufacturing programmes.
- Gap 3: Latency and connectivity resilience. The review found no controlled studies that quantify how network latency, bandwidth and intermittent connectivity affect cloud CAD performance. Research is needed to characterise these effects and to evaluate compensation strategies, such as predictive prefetching, differential update compression and offline-capable design continuation, for bandwidth-constrained environments.
- Gap 4: Scalable IP protection. Skeleton-model and partial-encryption approaches (Mun, Hwang and Han, 2009; Cai *et al.*, 2015; Cai *et al.*, 2017) have not been evaluated at production scale. The feasibility of stronger cryptographic approaches, such as homomorphic encryption or secure multi-party computation for selected geometric operations, has not been established.
- Gap 5: Standardised CAD-to-MES integration. The absence of standard protocols between cloud CAD platforms and MES forces each integration to be implemented as a bespoke project. Extensions of OPC UA companion specifications, or similar standards, to cover cloud-native product-model data would enable plug-and-play integration, building on the PLC–OPC–agent architectures already demonstrated for condition monitoring (Mashava *et al.*, 2026).
- Gap 6: Validated design–manufacture–operate digital twins. Conceptual frameworks abound (Tao *et al.*, 2018; Tao *et al.*, 2019b), but few have been validated across the full lifecycle in deployed industrial environments

(Kritzinger *et al.*, 2018). Longitudinal industrial case studies are needed, including studies that feed maintenance and reliability analytics (Senda *et al.*, 2026) back into design.

- Gap 7: Design rationale capture. The communication of design intent is inadequately supported by current platforms. Research is needed on structured rationale-capture mechanisms, potentially assisted by natural language processing and generative AI, that impose minimal documentation burden on engineers.
- Gap 8: Developing-economy contexts. Research addressing cloud CAD/CAM adoption barriers, adaptation strategies and performance in Africa, South Asia and Latin America is almost entirely absent. Infrastructure constraints, skills availability and economic conditions in these regions differ materially from those in advanced industrial economies (Muhla *et al.*, 2023; Muhla *et al.*, 2025b).

6.2 Proposed research agenda

Table 4 translates the eight gaps into research directions and suggests suitable methods.

Table 4: Research agenda derived from the identified gaps

Gap	Proposed research direction	Suggested methods
1	Develop and standardise a cloud-native model exchange format that preserves parametric history and PMI, with ISO 10303 sponsorship	Standards development; round-trip conformance testing
2	Design and evaluate scalable, cognitive-load-bounded awareness and task-allocation mechanisms for sessions with 10 or more concurrent users	Controlled experiments; industrial field trials
3	Quantify latency and bandwidth effects and test compensation strategies in bandwidth-constrained settings	Network emulation experiments; field studies in remote sites
4	Prototype and benchmark cryptographic IP protection for selected geometric operations	Design science; performance benchmarking
5	Develop an OPC UA companion specification for cloud-native CAD model data	Specification development; reference implementation
6	Conduct longitudinal case studies of design–manufacture–operate digital twins in at least two sectors	Multiple-case study; action research
7	Build and evaluate structured, AI-assisted design-rationale capture integrated into cloud CAD	Design science; controlled experiments on rework
8	Carry out cross-national comparative studies of cloud CAD/CAM adoption and performance, including Southern African manufacturers	Surveys; mixed-methods case studies

7 IMPLICATIONS FOR PRACTICE AND ENGINEERING EDUCATION

For practitioners, the taxonomy offers a structured way to match platforms to organisational priorities. Firms that need rapid concurrent concept development should weigh collaboration granularity (D2) most heavily, whereas firms that need controlled release to production should weigh manufacturing integration depth (D3) and interoperability (D4). In all cases, gains depend on deliberate work-process design (Phadnis *et al.*, 2021), clear permissioning (Cheng *et al.*, 2023) and governance of IP and data sovereignty (Esposito *et al.*, 2016). For SMEs in developing economies, a staged approach, in which an improvement area is identified, current systems are assessed, risks are evaluated and pilots are run before scaling up, is consistent with the Industry 4.0 implementation framework proposed for Zimbabwean manufacturers (Muhla *et al.*, 2025b) and with maturity-based transformation models (Schuh *et al.*, 2017).

For engineering education, cloud CAD/CAM lowers the cost of equipping students with industry-relevant tools and allows distributed team projects that mirror professional practice (Deng *et al.*, 2022). Learning factories, which are realistic production environments for experiential learning, provide a natural setting in which cloud design, CAM and shop-floor execution can be taught as a connected digital thread (Abele *et al.*, 2017). A staged framework for establishing a network of learning factories across Southern Africa, anchored on existing South African facilities, has been proposed to close the region's theory–practice gap (Ndiyamba *et al.*, 2026). Embedding cloud CAD/CAM, DOE-based process optimisation and condition-monitoring data within such facilities would allow students and industry partners to experience the full design–manufacture–operate loop described in Figure 3.

8 CONCLUSIONS

This systematic review examined 87 primary studies published between January 2016 and June 2026 on cloud-based CAD/CAM collaboration platforms in distributed manufacturing. Four principal contributions are made.

First, a four-dimensional taxonomy classifying platforms by architectural model, collaboration granularity, manufacturing integration depth and interoperability standard adherence provides a structured framework for comparing platforms and studies. Its application reveals a persistent trade-off between fine-grained real-time collaboration and deep manufacturing integration. Second, the synthesis of empirical evidence shows that cloud-native platforms enable new modes of concurrent work but that productivity and quality gains depend strongly on work-process design, team dynamics and permissioning. Robust longitudinal evidence from industrial deployments is still lacking. Third, the critical analysis indicates that the principal barriers to realising cloud CAD/CAM in distributed manufacturing are not the functional maturity of the platforms. They are the absence of standard formats for exchanging parametric models, the absence of standard CAD-to-MES integration protocols, insufficiently validated IP protection mechanisms, and the scarcity of evidence under the connectivity and skills conditions of developing economies. Fourth, eight research gaps and a corresponding agenda have been articulated for researchers, standardisation bodies and technology developers.

The review has limitations. It was restricted to English-language peer-reviewed literature, and the platform characterisation reflects a rapidly changing commercial landscape. Future updates should incorporate non-English CMfg literature and practitioner evidence. Future empirical work should, in particular, test cloud CAD/CAM under real Southern African operating conditions, where the authors' ongoing research in process optimisation, condition monitoring and learning factories provides a foundation for such studies.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

We acknowledge the Department of Industrial and Manufacturing Engineering Department of the National university of Science and Technology.

Disclosure of conflict of interest

The authors declare no conflict of interest.

REFERENCES

- [1] Abele, E., Chryssolouris, G., Sihn, W., Metternich, J., ElMaraghy, H., Seliger, G., Sivard, G., ElMaraghy, W., Hummel, V., Tisch, M. and Seifermann, S. (2017) 'Learning factories for future oriented research and education in manufacturing', *CIRP Annals*, 66(2), pp. 803–826. <https://doi.org/10.1016/j.cirp.2017.05.005>
- [2] Adamson, G., Wang, L., Holm, M. and Moore, P. (2017) 'Cloud manufacturing – a critical review of recent development and future trends', *International Journal of Computer Integrated Manufacturing*, 30(4–5), pp. 347–380. <https://doi.org/10.1080/0951192X.2015.1031704>
- [3] Badke-Schaub, P., Neumann, A., Lauche, K. and Mohammed, S. (2007) 'Mental models in design teams: a valid approach to performance in design collaboration?', *CoDesign*, 3(1), pp. 5–20. <https://doi.org/10.1080/15710880601170768>
- [4] Cai, X.T., He, F.Z., Li, W.D., Li, X.X. and Wu, Y.Q. (2015) 'Encryption based partial sharing of CAD models', *Integrated Computer-Aided Engineering*, 22(3), pp. 243–260. <https://doi.org/10.3233/ICA-150487>
- [5] Cai, X.T., Wang, S., Lu, X., Li, W.D. and Liang, Y.W. (2017) 'Parametric and adaptive encryption of feature-based computer-aided design models for cloud-based collaboration', *Integrated Computer-Aided Engineering*, 24(2), pp. 129–142. <https://doi.org/10.3233/ICA-160535>
- [6] Cheng, K., Davis, M.K., Zhang, X., Zhou, S. and Olechowski, A. (2023) 'In the age of collaboration, the computer-aided design ecosystem is behind: an interview study of distributed CAD practice', *Proceedings of the ACM on Human-Computer Interaction*, 7(CSCW1), pp. 1–29. <https://doi.org/10.1145/3579613>
- [7] Deng, Y., Mueller, M., Rogers, C. and Olechowski, A. (2022) 'The multi-user computer-aided design collaborative learning framework', *Advanced Engineering Informatics*, 51, 101446. <https://doi.org/10.1016/j.aei.2021.101446>
- [8] Ellis, C.A. and Gibbs, S.J. (1989) 'Concurrency control in groupware systems', *ACM SIGMOD Record*, 18(2), pp. 399–407. <https://doi.org/10.1145/66926.66963>

- [9] Esposito, C., Castiglione, A., Martini, B. and Choo, K.-K.R. (2016) 'Cloud manufacturing: security, privacy, and forensic concerns', *IEEE Cloud Computing*, 3(4), pp. 16–22. <https://doi.org/10.1109/MCC.2016.79>
- [10] Fuh, J.Y.H. and Li, W.D. (2005) 'Advances in collaborative CAD: the-state-of-the art', *Computer-Aided Design*, 37(5), pp. 571–581. <https://doi.org/10.1016/j.cad.2004.08.005>
- [11] Grieves, M. (2006) *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*. New York: McGraw-Hill.
- [12] He, W. and Xu, L. (2015) 'A state-of-the-art survey of cloud manufacturing', *International Journal of Computer Integrated Manufacturing*, 28(3), pp. 239–250. <https://doi.org/10.1080/0951192X.2013.874595>
- [13] Jansen, K.C., Mapindu, I., Muhla, T.M., Kanyemba, G. and Mashava, D. (2025) 'Optimization of edible oil quality through vacuum bleaching: an experimental design and analysis study', *Open Access Research Journal of Science and Technology*, 13(2), pp. 68–78. <https://doi.org/10.53022/oarjst.2025.13.2.0051>
- [14] Kim, J., Pratt, M.J., Iyer, R.G. and Sriram, R.D. (2008) 'Standardized data exchange of CAD models with design intent', *Computer-Aided Design*, 40(7), pp. 760–777. <https://doi.org/10.1016/j.cad.2007.06.014>
- [15] Kitchenham, B. and Charters, S. (2007) *Guidelines for Performing Systematic Literature Reviews in Software Engineering*. EBSE Technical Report EBSE-2007-01. Keele: Keele University and Durham University.
- [16] Kleinsmann, M., Buijs, J. and Valkenburg, R. (2010) 'Understanding the complexity of knowledge integration in collaborative new product development teams: a case study', *Journal of Engineering and Technology Management*, 27(1–2), pp. 20–32. <https://doi.org/10.1016/j.jengtecman.2010.03.003>
- [17] Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihn, W. (2018) 'Digital twin in manufacturing: a categorical literature review and classification', *IFAC-PapersOnLine*, 51(11), pp. 1016–1022. <https://doi.org/10.1016/j.ifacol.2018.08.474>
- [18] Lasi, H., Fettke, P., Kemper, H.-G., Feld, T. and Hoffmann, M. (2014) 'Industry 4.0', *Business & Information Systems Engineering*, 6(4), pp. 239–242. <https://doi.org/10.1007/s12599-014-0334-4>
- [19] Li, B.H., Zhang, L., Wang, S.L., Tao, F., Cao, J.W., Jiang, X.D., Song, X. and Chai, X.D. (2010) 'Cloud manufacturing: a new service-oriented networked manufacturing model', *Computer Integrated Manufacturing Systems*, 16(1), pp. 1–7.
- [20] Li, W.D., Lu, W.F., Fuh, J.Y.H. and Wong, Y.S. (2005) 'Collaborative computer-aided design—research and development status', *Computer-Aided Design*, 37(9), pp. 931–940. <https://doi.org/10.1016/j.cad.2004.09.020>
- [21] Lipman, R. and Lubell, J. (2015) 'Conformance checking of PMI representation in CAD model STEP data exchange files', *Computer-Aided Design*, 66, pp. 14–23. <https://doi.org/10.1016/j.cad.2015.04.002>
- [22] Mapindu, I., Foya, A., Muhla, T.M., Chinguwo, K.N. and Kanyemba, G. (2026a) 'Minimizing defects in injection molding using the Taguchi method', *World Journal of Advanced Engineering Technology and Sciences*, 20(2), pp. 240–252. <https://doi.org/10.30574/wjaets.2026.20.2.0419>
- [23] Mapindu, I., Muhla, T.M., Chinguwo, K.N. and Foya, A. (2026b) 'Process parameter optimization for 3D printing using the Taguchi method', *Open Access Research Journal of Science and Technology*, 18(1), pp. 34–45. <https://doi.org/10.53022/oarjst.2026.18.1.0082>
- [24] Mapindu, I., Munhuwamambo, G., Mashava, D. and Ngwenya, L. (2026c) 'Optimization of cutting parameters in CNC milling using the Taguchi method', *Global Journal of Engineering and Technology Advances*, 28(2), pp. 149–162. <https://doi.org/10.30574/gjeta.2026.28.2.0223>
- [25] Mapindu, I., Mashava D., Shangwa, V., Chigavazira-Gwara, T.T., Munhuwamambo, G (2026d) 'Taguchi-based optimization of GMAW welding parameters for joint strength', *World Journal of Advanced Engineering Technology and Sciences*, 20(3), pp. 206–219. Available at: <https://doi.org/10.30574/wjaets.2026.20.3.0448>
- [26] Mashava, D., Muhla, T.M., Munhuwamambo, G., Mapindu, I., Chinguwo, K.N. and Wachenuka, T. (2026) 'A multi-agent system framework for real-time self-diagnostic condition monitoring of induction furnace equipment in developing industrial economies', *Open Access Research Journal of Science and Technology*, 17(2), pp. 28–43. <https://doi.org/10.53022/oarjst.2026.17.2.0071>
- [27] Mell, P. and Grance, T. (2011) *The NIST Definition of Cloud Computing*. NIST Special Publication 800-145. Gaithersburg, MD: National Institute of Standards and Technology. <https://doi.org/10.6028/NIST.SP.800-145>
- [28] Mourtzis, D., Vlachou, E., Xanthopoulos, N., Givehchi, M. and Wang, L. (2016) 'Cloud-based adaptive process planning considering availability and capabilities of machine tools', *Journal of Manufacturing Systems*, 39, pp. 1–8. <https://doi.org/10.1016/j.jmsy.2016.01.003>

- [29] Muhla, T., Kanyemba, G., Mapindu, I., Chinguwo, N., Mashava, D. and Goriwondo, W. (2025a) 'Enhancing safety in Zimbabwean manufacturing industry: the role of human factors engineering in reducing workplace accidents', *Open Access Research Journal of Science and Technology*, 13(2), pp. 19–30. <https://doi.org/10.53022/oarjst.2025.13.2.0037>
- [30] Muhla, T., Mapindu, I., Munyau, M., Mashava, D., Mhlanga, S. and Goriwondo, W. (2023) 'Agility as a strategy in Zimbabwean manufacturing industries', *Zimbabwe Journal of Science & Technology*, 18, pp. 1–11.
- [31] Muhla, T.M., Mashava, D., Kanyemba, G., Mapindu, I. and Goriwondo, W.M. (2025b) 'An assessment of the implementation of Industry 4.0 in Zimbabwean manufacturing industries', *World Journal of Advanced Engineering Technology and Sciences*, 15(2), pp. 970–984. <https://doi.org/10.30574/wjaets.2025.15.2.0653>
- [32] Mun, D., Hwang, J. and Han, S. (2009) 'Protection of intellectual property based on a skeleton model in product design collaboration', *Computer-Aided Design*, 41(9), pp. 641–648. <https://doi.org/10.1016/j.cad.2009.04.007>
- [33] Munotyaaani, S., Bawono, N.M.H., Tayisepi, N., Mapindu, I., Anggoro, P.W., Bawono, B., Pamosoaji, A.K. and Adi, A.Y.N.M.P. (2026) 'Design and development of a dual-mode smart wheelchair prototype with obstacle detection for Zimbabwe', *Jurnal Rekayasa Mesin*, 21(1), pp. 51–66. <https://doi.org/10.32497/jrm.v21i1.6954>
- [34] Muyambo, R.D., Muhla, T., Kanyemba, G., Mashava, D., Munhuwamambo, G. and Mapindu, I. (2025) 'Design and development of a vertical axis wind turbine for slip stream energy harvesting', *Global Journal of Engineering and Technology Advances*, 23(3), pp. 10–20. <https://doi.org/10.30574/gjeta.2025.23.3.0166>
- [35] Ndiyamba, D., Murena, E., Kasukusa, S., Mafuratidze, F., Nenzhelele, T., Mpofu, K. and Mapindu, I. (2026) 'Learning factories as a catalyst for innovation in Southern African engineering education', in Rauch, E., Matt, D.T., Kerschbaumer, W., Dallasega, P., Gualtieri, L. and De Marchi, M. (eds) *CLF 2026 Book of Short Papers on Learning Factories: Proceedings of the 16th Conference on Learning Factories*. Bolzano: Free University of Bozen-Bolzano, pp. 93–99. <https://doi.org/10.5281/zenodo.20780648>
- [36] Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D. *et al.* (2021) 'The PRISMA 2020 statement: an updated guideline for reporting systematic reviews', *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- [37] Phadnis, V., Arshad, H., Wallace, D. and Olechowski, A. (2021) 'Are two heads better than one for computer-aided design?', *Journal of Mechanical Design*, 143(7), 071401. <https://doi.org/10.1115/1.4050734>
- [38] Qi, Q. and Tao, F. (2018) 'Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison', *IEEE Access*, 6, pp. 3585–3593. <https://doi.org/10.1109/ACCESS.2018.2793265>
- [39] Red, E., Holyoak, V., Jensen, C.G., Marshall, F., Ryskamp, J. and Xu, Y. (2010) 'v-CAX: a research agenda for collaborative computer-aided applications', *Computer-Aided Design and Applications*, 7(3), pp. 387–404. <https://doi.org/10.3722/cadaps.2010.387-404>
- [40] Ren, L., Zhang, L., Tao, F., Zhao, C., Chai, X. and Zhao, X. (2015) 'Cloud manufacturing: from concept to practice', *Enterprise Information Systems*, 9(2), pp. 186–209. <https://doi.org/10.1080/17517575.2013.839055>
- [41] Ren, L., Zhang, L., Wang, L., Tao, F. and Chai, X. (2017) 'Cloud manufacturing: key characteristics and applications', *International Journal of Computer Integrated Manufacturing*, 30(6), pp. 501–515. <https://doi.org/10.1080/0951192X.2014.902105>
- [42] Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M. and Wahlster, W. (eds) (2017) *Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies*. acatech STUDY. Munich: Herbert Utz Verlag.
- [43] Senda, S., Muhla, T.M., Mapindu, I., Ngwenya, L., Mushangure, R.O. and Mashava, D. (2026) 'Machine learning enabled preventive maintenance strategy for improving boiler reliability of a thermal power station', *Open Access Research Journal of Science and Technology*, 17(2), pp. 18–27. <https://doi.org/10.53022/oarjst.2026.17.2.0070>
- [44] Stark, J. (2015) *Product Lifecycle Management (Volume 1): 21st Century Paradigm for Product Realisation*. 3rd edn. Cham: Springer. <https://doi.org/10.1007/978-3-319-17440-2>
- [45] Stone, B., Salmon, J.L., Eves, K., Killian, M., Wright, L., Oldroyd, J., Gorrell, S. and Richey, M.C. (2017) 'A multi-user computer-aided design competition: experimental findings and analysis of team-member dynamics', *Journal of Computing and Information Science in Engineering*, 17(3), 031003. <https://doi.org/10.1115/1.4035674>
- [46] Tandii, O., Mapindu, I., Muhla, T.M., Chinguwo, N.K. and Tayisepi, N. (2025) 'Design and analysis of a passive upper limb exoskeleton for augmented construction worker strength', *Open Access Research Journal of Science and Technology*, 13(2), pp. 79–88. <https://doi.org/10.53022/oarjst.2025.13.2.0050>
- [47] Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H. and Sui, F. (2018) 'Digital twin-driven product design, manufacturing and service with big data', *International Journal of Advanced Manufacturing Technology*, 94(9–12), pp. 3563–3576. <https://doi.org/10.1007/s00170-017-0233-1>

- [48] Tao, F., Qi, Q., Wang, L. and Nee, A.Y.C. (2019a) 'Digital twins and cyber-physical systems toward smart manufacturing and Industry 4.0: correlation and comparison', *Engineering*, 5(4), pp. 653–661. <https://doi.org/10.1016/j.eng.2019.01.014>
- [49] Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2019b) 'Digital twin in industry: state-of-the-art', *IEEE Transactions on Industrial Informatics*, 15(4), pp. 2405–2415. <https://doi.org/10.1109/TII.2018.2873186>
- [50] Tao, F., Zhang, L., Venkatesh, V.C., Luo, Y. and Cheng, Y. (2011) 'Cloud manufacturing: a computing and service-oriented manufacturing model', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 225(10), pp. 1969–1976. <https://doi.org/10.1177/0954405411405575>
- [51] Tayisepi, N., Mugwagwa, L., Mnkandla, A.N., Mapindu, I. and Muhla, T.M. (2024) 'Experimental investigation and simultaneous optimisation of honing parameters of dry cast iron cylinder relining sleeves of motor vehicle engine blocks for surface finish and energy use', *Computational Engineering and Physical Modeling*, 7(4), pp. 88–103. <https://doi.org/10.22115/cepm.2024.473138.1324>
- [52] Tayisepi, N., Svosve, R., Tigere, G., Mnkandla, A.N. and Mapindu, I. (2023) 'Comparative optimisation of the cutting parameters for surface quality and energy efficiency during the machining manufacturing of teak, saligna and pine wood materials', *Journal of Engineering Research and Reports*, 25(11), pp. 73–87. <https://doi.org/10.9734/IJERR/2023/v25i1111023>
- [53] Thomas, J. and Harden, A. (2008) 'Methods for the thematic synthesis of qualitative research in systematic reviews', *BMC Medical Research Methodology*, 8, 45. <https://doi.org/10.1186/1471-2288-8-45>
- [54] Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a methodology for developing evidence-informed management knowledge by means of systematic review', *British Journal of Management*, 14(3), pp. 207–222. <https://doi.org/10.1111/1467-8551.00375>
- [55] Wang, X.V. and Xu, X.W. (2013) 'An interoperable solution for cloud manufacturing', *Robotics and Computer-Integrated Manufacturing*, 29(4), pp. 232–247. <https://doi.org/10.1016/j.rcim.2013.01.005>
- [56] Whitney, D.E. (2004) *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York: Oxford University Press.
- [57] Wohlin, C. (2014) 'Guidelines for snowballing in systematic literature studies and a replication in software engineering', in *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering (EASE '14)*. London: ACM, Article 38. <https://doi.org/10.1145/2601248.2601268>
- [58] Wu, D., Rosen, D.W., Wang, L. and Schaefer, D. (2015) 'Cloud-based design and manufacturing: a new paradigm in digital manufacturing and design innovation', *Computer-Aided Design*, 59, pp. 1–14. <https://doi.org/10.1016/j.cad.2014.07.006>
- [59] Xu, L.D., Xu, E.L. and Li, L. (2018) 'Industry 4.0: state of the art and future trends', *International Journal of Production Research*, 56(8), pp. 2941–2962. <https://doi.org/10.1080/00207543.2018.1444806>
- [60] Xu, X. (2012) 'From cloud computing to cloud manufacturing', *Robotics and Computer-Integrated Manufacturing*, 28(1), pp. 75–86. <https://doi.org/10.1016/j.rcim.2011.07.002>
- [61] Zhong, R.Y., Xu, X., Klotz, E. and Newman, S.T. (2017) 'Intelligent manufacturing in the context of Industry 4.0: a review', *Engineering*, 3(5), pp. 616–630. <https://doi.org/10.1016/I.ENG.2017.05.015>