



COMPUTER-AIDED PROCESS PLANNING AND ITS INTEGRATION WITH ERP AND MRP SYSTEMS: A SYSTEMATIC REVIEW

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Open Access Research Journal of Science and Technology, 2026, 18(01), 073–085

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.2026.18.1.0089>

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ABSTRACT

In today's manufacturing industry, Computer-Aided Process Planning (CAPP) is an important tool that helps to convert design information into manufacturing plans efficiently. With the changing dynamics of manufacturing environments with a greater focus on digital integration, integration of CAPP with Enterprise Resource Planning (ERP) and Material Requirements Planning (MRP) systems becomes significant to achieve operational efficiency. This systematic review is a review of current status and the challenges of digital integration of the CAPP and ERP/MRP systems in the context of Computer Integrated Manufacturing (CIM). The purpose of this paper is to shed light on the dominant approaches, challenges of integration, benefits, and technology trends that emerged from various studies. The aim of the review is to create an organised knowledge base for researchers and practitioners that will help them to make the process planning workflow more optimised, by using better ERP and MRP integration, to set in motion improved resource utilization, production scheduling and decision making. The review is conducted following a documented protocol, according to PRISMA. The CAPP terms were searched in Scopus, Web of Science, IEEE Xplore, ScienceDirect and Google Scholar along with ERP, MRP, integration and interoperability terms and only the peer-reviewed English literature published from 2016 to 2025 were included. Titles, abstracts and full texts were screened by two reviewers against pre-stated eligibility criteria, data was extracted on a standard form, the quality of the studies was appraised with a checklist and the 22 included studies were organised on a taxonomy of integration level, CAPP approach (variant, generative, hybrid), enterprise-system scope, enabling technology, and application domain. The synthesis reveals a transition towards STEP-based data exchange, service-oriented architectures, ontology-based and digital-twin architectures, but little evidence of end-to-end integration, especially for SMEs and manufacturers in developing countries. The review is offered as a guide for researchers and practitioners interested in making a step towards closing the gap between design and process planning and enterprise planning.

Keywords: Computer Aided Process Planning, ERP, MRP,

1 INTRODUCTION

Computer-Aided Process Planning (CAPP) is used to create process plans for manufacture from product design data and Material Requirements Planning (MRP) and Enterprise Resource Planning (ERP) are used for material, production and enterprise planning. The integration of these systems within the Computer-Integrated Manufacturing (CIM) context

could help to enhance information transfer from the design stage to the production stage. The implementation of integration, however, is difficult due to the difference in software architectures, data structures and information needs. In much CAPP research process-plan generation is the focus, whereas the data from MRP and ERP is regarded as given. As a result, manual data transfer, customised interfaces are still widely used. Issues are more salient in the developing industrial economies.

When surveyed, most of the manufacturers in Zimbabwe reported no Industry 4.0 strategy, enabling technologies like computers, sensors and programmable logic controllers were already being applied, but were not necessarily well integrated (Muhla et al., 2025a). Another precondition for manufacturing agility is the ability to reconfigure manufacturing resources rapidly when the customer's requirements change, which is possible by integrated planning (Muhla et al., 2023). However, the majority of published integration frameworks are tested in large, well-resourced companies. This systematic review therefore investigates CAPP integration with MRP and ERP, highlighting integration approaches, enablers technologies, reported value, problems and gaps, and provides explicit attention to constraints of small and medium sized enterprises (SMEs) and resource constrained environments.

2 BACKGROUND AND THEORETICAL FOUNDATION

The Computer-Aided Process Planning (CAPP) is a computer technology application that transforms product design information into manufacturing process plans, which include the process operations, the sequence of operations, the machines, and the resources. CAPP can be variants, generative or hybrid as plans can be retrieved, generated from manufacturing knowledge or a combination of both. It plays the major role in the creation of manufacturing information which can be conveyed to the production planning and enterprise systems which are its major concern in this study.

Computer-Integrated Manufacturing (CIM) is the concept of bringing together design, process planning, production and business functions via information systems. In CIM, CAPP is the connection of engineering systems like CAD and production-management systems like MRP, ERP and MES. Accurate, timely and consistent information exchange is key to effective integration. MRP calculates the requirements for materials and when they are needed based on production schedules, bills of materials, inventory and lead time data. This extends to other business functions like production, purchasing, inventory and finance in ERP. To effect a

CAPP/MRP/ERP integration, manufacturing information (routings, operations and resource needs) must be exchanged effectively between systems. Among the various approaches to CAPP–ERP–MRP integration, the database exchange, middleware, standardised interfaces, web services, and ontology-based approaches are considered. This study is based on the CIM and systems-integration principles with emphasis on the information flow, interoperability, consistency and coordination of information between engineering and enterprise systems. These concepts serve as the foundation for a theoretical framework of the integration approaches, benefits and challenges reported in the literature.

Aim

This review aims to analyse research on CAPP integration with ERP and MRP systems, identifying key approaches, benefits, barriers and research gaps.

2.1 RESEARCH QUESTIONS

- What are the main challenges in achieving seamless integration?
- How does the integration of these systems align with one another and support the aims of the CIM framework?
- What are the strategies and technologies used to integrate CAPP with ERP and MRP systems?
- What benefits have been seen by companies adopting integrated CAPP–ERP/MRP solutions?

Objectives

- To provide a comprehensive synthesis of existing literature on CAPP and its integration with ERP and MRP systems.
- To identify gaps in research and practical implementation barriers.
- To highlight emerging trends and promising approaches that could enhance integration.
- To offer recommendations for future research directions and practical strategies to improve CAPP-ERP/MRP interoperability.

3 METHODOLOGY AND SEARCH STRATEGY

This review is conducted in a systematic manner, following a reporting guideline called PRISMA 2020 (Page et al., 2021) to ensure that the search, screening and selection process is transparent and reproducible by an independent

researcher. The protocol consists of three phases: a documented multiple-database search using controlled boolean strings, two phases of screening (one based on explicit inclusion criteria and one based on explicit exclusion criteria), and full text eligibility screening before inclusion in the synthesis.

3.1 Databases and Search Strings

The following sources were used for a balance of indexed coverage for academic disciplines with engineering-specific and grey literature: Scopus and Web of Science for broad multidisciplinary coverage, IEEE Xplore for control- and systems-engineering contributions and ScienceDirect for manufacturing-engineering journals, and Google Scholar for citation snowballing. Search strings were made up of three concept blocks with Boolean AND: (CAPP terms) AND (ERP/MRP terms) AND (integration terms), which were shortened and modified for each database's syntax as shown in Table 1.

Table 1: Databases, search strings, and applied filters

Database	Search string (Boolean)	Field / Filters applied	Date range
Scopus	("computer-aided process planning" OR CAPP) AND ("ERP" OR "enterprise resource planning" OR "MRP" OR "material requirements planning") AND (integration OR interoperability)	Title, Abstract, Keywords; Article, Review; English	2016–2025
Web of Science	TS=(("process planning" AND CAPP) AND (ERP OR MRP) AND (integrat* OR interoperab* OR "data exchange"))	Topic search; Core Collection	2016–2025
IEEE Xplore	("Computer Aided Process Planning" OR CAPP) AND ("ERP" OR "MRP") AND (framework OR architecture OR integration)	Full-text and metadata	2016–2025
ScienceDirect	"process planning" AND ("enterprise resource planning" OR "material requirements planning") AND integration	Research articles; Engineering & Manufacturing	2016–2025
Google Scholar	"CAPP" "ERP" "MRP" integration OR interoperability (used for snowballing / grey-literature check)	First 100 results, sorted by relevance	2016–2025

3.2 Inclusion and Exclusion Criteria

To keep the corpus focused on the technical integration problem rather than on CAPP, ERP, or MRP as standalone topics, records were retained only where the integration linkage was explicit and verifiable. Table 2 summarises the criteria applied at both the screening and eligibility stages.

Table 2: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles and indexed conference papers published 2016–2025	Publications before 2016, textbooks, editorials, and non-peer-reviewed sources
Explicit technical focus on CAPP and its data or process linkage to ERP and/or MRP systems	Studies treating CAPP, ERP, or MRP as isolated systems with no integration dimension
Full text available in English	Duplicate records across databases; abstract-only or inaccessible full text

Reports an architecture, framework, model, data standard, or empirical case of integration	Purely commercial/vendor whitepapers with no verifiable methodology
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3.3 Screening Process (PRISMA Flow)

Records retrieved from all sources were pooled, de-duplicated, and screened in two passes: a title/abstract pass to remove clearly irrelevant records, followed by full-text assessment against the eligibility criteria. Figure 1 illustrates this flow and the resulting corpus size at each stage.

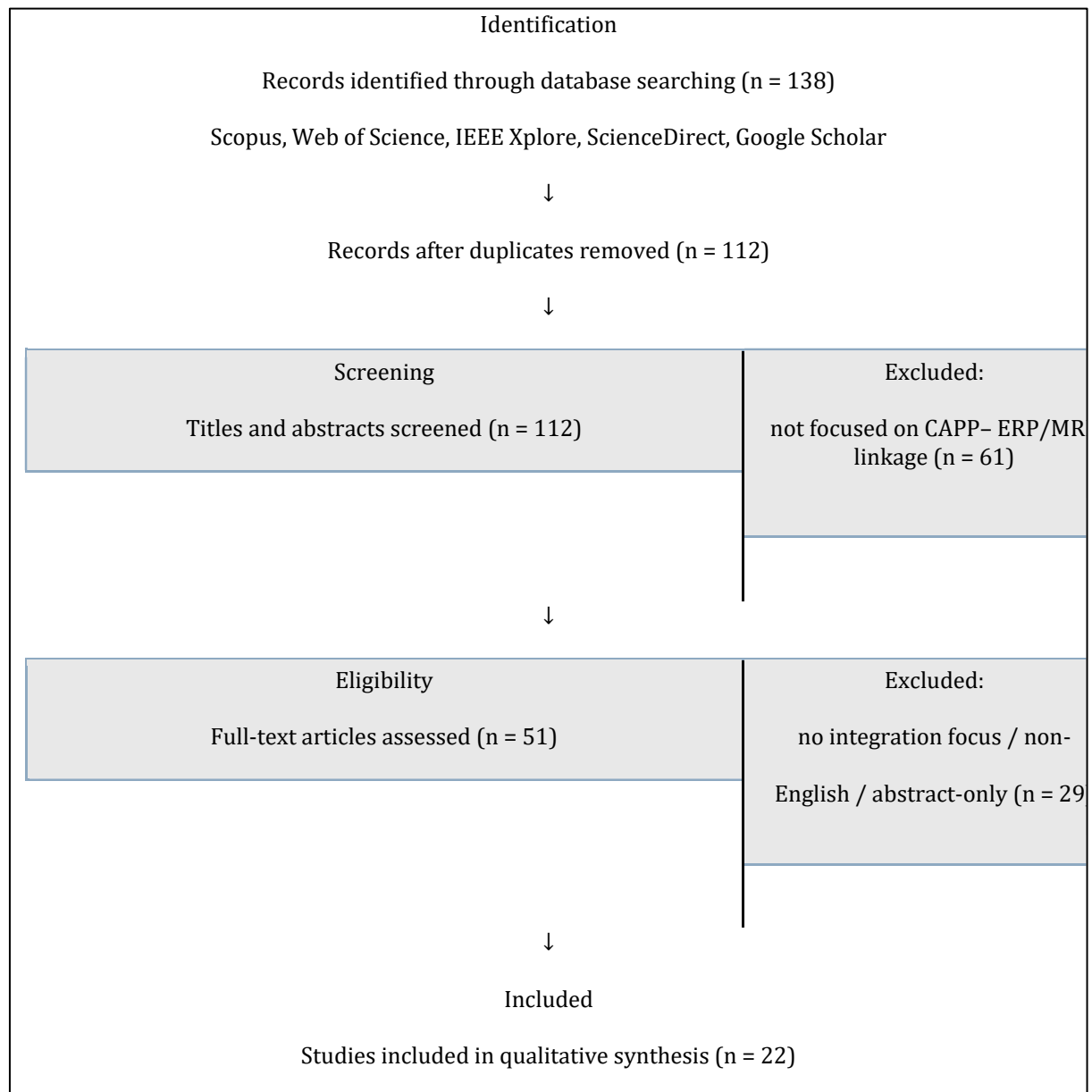


Figure 1: PRISMA flow diagram of record identification, screening and inclusion (adapted from the PRISMA 2020 flow diagram template; Page et al., 2021)

4 CLASSIFICATION AND TAXONOMY

The 22 studies in the corpus were coded and systematised into a taxonomy following six dimensions that were consistently found across the studies: the CAPP approach adopted, the integration architecture used to link CAPP and ERP/MRP, the data exchange standard for the integration, the functional scope of the integration, the industrial application domain and the time period, tracing the evolution of the prevailing integration paradigm since 2016. The combination of these dimensions shows that early research (2016-2018) focused on addressing fundamental interoperability issues related to data, largely by adopting neutral formats (STEP), while more recent research (2022-

2025) is directed towards service-oriented, cloud-based and AI-influenced architectures that align to the Industry 4.0 and digital-thread paradigm. The resulting classification framework is shown in Table 3.

Table 3: Classification and taxonomy of the reviewed literature on CAPP–ERP/MRP integration

Classification dimension	Categories identified	Representative focus
By CAPP approach	Variant; Generative; Semi-generative (hybrid); Knowledge/rule-based; AI-assisted (ML/GA/agent-based)	How process plans are derived before being passed to planning systems
By integration architecture	Direct/point-to-point interfacing; Middleware or service-oriented (SOA) integration; Shared/common database; Cloud- and platform-based (Industry 4.0)	The technical mechanism connecting CAPP to ERP/MRP
By data exchange standard	STEP/STEP-NC (ISO 10303); XML/B2MML schemas; Proprietary APIs; Ontology-based semantic models	How process, product, and resource data are represented and transferred
By functional scope	Routing/BOM synchronisation; Capacity and lead-time feedback to MRP; Cost/time estimation; Closed-loop scheduling	Which planning function the integration is built to support
By application domain	Discrete machining/job-shop; Automotive; Aerospace; SME manufacturing; Process/continuous industries	Industrial context in which the framework was validated
By time period	2016–2018: interoperability and STEP-based exchange; 2019– 2021: SOA/cloud integration; 2022–2025: Industry 4.0, digital-thread and AI-driven integration	Evolution of the dominant integration paradigm over the review window

This taxonomy is used in the subsequent sections of the review to structure the synthesis: studies are compared within each category to surface points of convergence (e.g., the near-universal reliance on Bill-of-Materials and routing data as the shared interface between CAPP and MRP) and points of contradiction (e.g., disagreement over whether generative CAPP or knowledge-based CAPP integrates more reliably with commercial ERP suites), which are discussed further in the results and discussion sections.

5 CRITICAL ANALYSIS AND SYNTHESIS

5.1 Literature Review

Digital technologies have made manufacturing a connected world where the design, production process, materials management and enterprise functions share information across the entire manufacturing system. In this context, Computer-Aided Process Planning (CAPP) is very useful since it converts the information of a product design into the corresponding manufacturing instructions. It thus serves as a bridge between Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), production planning and enterprise systems like Material Requirements Planning (MRP), Manufacturing Resource Planning (MRP II) and Enterprise Resource Planning (ERP) (Al-wswasi, Ivanov and Makatsoris, 2018). CAPP, MRP and ERP are complementary but have different functions.

CAPP defines the operations, sequences, machines, tools and processing requirements for the manufacture of a product. MRP identifies materials needed, their quantities, and their timelines, while ERP connects production with other organizational tasks like procurement, inventory, finance and supply-chain management. These systems can be integrated to enhance consistency of information, minimize duplicate data entry and enable more effective and unified production planning. But despite progress on data structures and interoperability, integration remains difficult because of data quality and data readiness issues in organisations. These are in the context of the broader Industry 4.0 program. Several reviews trace the changes of manufacturing systems driven by the design principles identified by Hermann, Pentek and Otto (2016) for Industrie 4.0 scenarios, which include interoperability, virtualisation, decentralisation, real-

time capability, service orientation and modularity (Liao et al., 2017; Pereira and Romero, 2017; Zhong et al., 2017; Xu, Xu and Li, 2018).

It would be useful for locating CAPP–ERP/MRP integration at the integration level of the framework proposed by Qin, Liu and Grosvenor (2016) from control to integration to intelligence levels along machine, process and factory. Empirical studies have also demonstrated that adoption is implemented in a specific way (Frank, Dalenogare and Ayala, 2019), that it is interwoven with lean production (Tortorella and Fettermann, 2018), and that it has positive and negative effects for organisations (Sony, 2020). As integration affects not just data flows but also work practices, it is also a socio-technical project (Sony and Naik, 2020) that has implications for resource efficiency and sustainability (Ghobakhloo, 2020). Consistency of data flow throughout the life cycle of the product is another key requirement for data-driven SM, as all three systems of CAPP, MRP and ERP are designed to do.

5.2 Computer-Aided Process Planning

Computer-Aided Process Planning (CAPP) is a computer-based application that facilitates and automates manufacturing process planning, which minimizes manual process planning (Okpala and Okonkwo, 2018). There are variant and generative approaches to traditional CAPP. CAPP is a variant which changes plans to cater for planning time reduction and standardisation, but requires appropriate planning to be in place beforehand. Generative CAPP generates plans by means of rules, databases and algorithms that in turn are more flexible, but need precise manufacturing knowledge and data (Okpala and Okonkwo, 2018; Al-wswasi, Ivanov and Makatsoris, 2018).

Generative or knowledge-based plans are more or less good depending on how well the plan embodies the manufacturing knowledge; and much of this knowledge is parameter-level. The Taguchi method and analysis of variance, combined with grey relational analysis, have been used to design experiments and validated parameter windows for CNC milling (Mapindu et al., 2026b), plastic injection moulding (Mapindu et al., 2026a), fused deposition modelling (Mapindu et al., 2026c), weld parameter optimization (Mapindu et al., 2026d) and other experimentally designed processes such as honing of cylinder relining sleeves (Tayisepi et al., 2024) and machining of hardwoods and softwoods (Tayisepi et al., 2023); a vacuum bleaching process in edible oil refinement has been designed using similar experimental modelling (Jansen et al., 2025).

This work has two findings that are relevant to integration. The optimal settings were specific to the machine–tool–material combination and could not be easily transferred from one study to another (Mapindu et al., 2026b; Mapindu et al., 2026c), meaning that knowledge bases for the CAPP should be based on locally validated data and not merely on generic handbook values. Secondly, energy use and cycle time were sensitive to parameters that were set at the planning stage, which implies that process plan includes cost, time and energy information which is also needed for ERP costing and MRP lead-time calculation. The CAPP research is advancing in the recent years through different approaches: artificial intelligence, knowledge graphs, immersive environments and optimisation, that are used in order to improve process planning (Rojek, 2017; Soori and Asmael, 2021; Zhou and Camba, 2021; Xiao et al., 2023).

There is, however, only a little research that explores how the outputs of CAPP are coupled with MRP and ERP, which is an important research gap. Recent CAPP research uses artificial intelligence, knowledge graphs, immersive environments and optimisation to improve process planning (Rojek, 2017; Soori and Asmael, 2021; Zhou and Camba, 2021; Xiao et al., 2023). However, limited research examines how CAPP outputs integrate with MRP and ERP, highlighting an important research gap.

5.3 Relationship between CAPP, MRP and ERP

CAPP, MRP and ERP are complementary manufacturing systems. CAPP translates the product information into manufacturing information, MRP determines the materials requirements and ERP integrates these functions with other business processes (Kiran, 2019; Najy, 2020). CAD is followed by CAPP and then MRP/MRP II and then ERP and then Manufacturing. Figure 2. Simplified product design to enterprise planning (authors' own construction, based on the functional relationships described by Kiran, 2019). CAPP offers routings, operation sequences, machines, and processing time and resource requirements for scheduling, capacity planning and costing (Jaskó et al., 2020). But integration is complex in other databases and data structures, which makes it essential to have a reliable data exchange between CAPP–MRP–ERP. The product structure and material data generated during the design process are used by both CAPP and MRP in the upstream. CAD models, finite element or computational fluid dynamics analyses, functional decomposition and costed bills of materials were generated in different tools in design studies like passive upper-limb exoskeleton (Tandi et al., 2025), vertical axis wind turbine for slipstream energy harvesting (Muyambo et al., 2025), and dual-mode smart wheelchair (Munotyaani et al., 2026). These products get to production and the same information needs to be re-entered as BOMs and routings in planning systems, thus showcasing the information duplication and error-prevention that CAPP–ERP/MRP integration aims to eliminate.

5.4 Integration Technologies and Digital Manufacturing

The combined use of CAPP, MRP and ERP is implemented in the larger framework of Computer-Integrated Manufacturing (CIM) and Industry 4.0. CIM aims to integrate computer based systems throughout manufacturing process to enable information flow among design, planning, production and enterprise activities (Soori and Asmael, 2021). One of the big problems is that manufacturing companies have disparate systems created at different times and with different data structures. Kutin et al. (2018) point out issues with integration of systems having differing architectures and information models.

There are also various standards like ISA-95 and B2MML that can be used to establish structured communication between enterprise and manufacturing systems, but there are also customised and point-to-point interfaces (Jaskó et al., 2020). The problem of standards and reference architectures is at the very core of this problem. An analysis of the standards environment and the architecture for smart manufacturing reveals the complexity of multiple overlapping standards in product, process and enterprise data (Lu, Morris and Frechette, 2016; Ford, 2018) and the need for standardisation as the key challenge for modular, multi-vendor production systems (Weyer et al., 2015).

MES are a system located between process planning and ERP, and today intelligent MES are expected to play a mediator role between them (Shojaeinasab et al., 2022). On the enterprise side, the reviews of ERP in the Industry 4.0 context reveal the integration between ERP and shop-floor and cyber-physical systems (Balaha et al., 2025) and the inclusion of process-level inventory data when LCI is associated with the ERP (Ferrari et al., 2020). In resource-constrained plants, industrial middleware is a viable path for such connections.

In a Zimbabwean foundry, Mashava et al (2026) used commercial off-the-shelf (COTS) components, such as field sensors, a Siemens S7-1200 programmable logic controller (PLC), an OPC server that was vendor-independent, a JADE multi-agent platform, a MySQL database and automated alerts. The same paradigm of OPC connectivity and agent-based messaging may be used to move CAPP routings, machine status, machine capacity information from the shop to ERP/MRP, although that system was used for condition monitoring and not process planning. Another method is semantic integration which allows different systems to have a common understanding of the meaning of manufacturing information. Seeharit, Šormaz and Fuloria (2025) show the potential of ontology-based approaches to connect to ERP data and information from the CAPP process-plan.

These are semantic foundations that can be found in product-driven ontologies, like ONTO-PDM (Panetto, Dassisti and Tursi, 2012), and in knowledge graphs, as in process planning (Xiao et al., 2023). This is crucial because operations, resources and routings can be different representations in the same systems for the same manufacturing activities. The digital thread offers a wider context for ensuring connected product and manufacturing information throughout the full product life cycle. Hedberg et al. (2016) carried out tests of the digital thread with a focus on model-based manufacturing and inspection, and Mies, Marsden and Warde (2016) highlight the need for the linkage of product, material, process and performance information. This means for CAPP and ERP to be maintained, information shall be traceable from the design, to the process planning, to production and enterprise management.

Digital twins are an extension of the digital thread as they maintain a virtual replica of the system that is synchronised with the physical system. Kritzing et al. (2018) categorize digital models, shadows and twins according to how automatic the data flow between the physical and virtual objects is, a distinction picked up by Wooley, Silva and Bitencourt (2023). The concept and its industrial applications are reviewed (Tao et al., 2019; Jones et al., 2020; Soori, Arezoo and Dastres, 2023; Yao et al., 2023; Seipolt, Buschermöhle and Hasselbring, 2025), and framework and standardisation are undertaken to establish common reference models (Shao and Helu, 2020; Shao, 2024; Shao, Kibira and Frechette, 2024).

Of particular relevance are the following applications of twins to the planning of functions: digital-twin-driven machining (Liu, Bao and Zheng, 2023), predictive maintenance (Aivaliotis, Georgoulas and Chrysosouris, 2019), integrated production and maintenance planning (Fede, Sgarbossa and Paltrinieri, 2024), dynamic production scheduling (Ouahabi et al., 2024), and factory and production planning throughout the factory lifecycle (Cieply et al., 2023; Burggräf, Adlon and Schäfer, 2024; Raheem, De Marchi and Dallasega, 2025). According to Afif and Sarhan (2025), CAPP, digital twins and smart manufacturing are interconnected in the case of CNC machining, suggesting the potential for digital twins as a link between process planning and enterprise-level planning. In CNC machining, Afif and Sarhan (2025) explain how digital twins are connected with CAPP and smart manufacturing, leading to the possibility of digital twins being used as a bridge between process planning and enterprise-level planning. So integration is not just about software integration, but about many other things. It requires data interoperability, common standards, semantic consistency, traceability and appropriate system architectures.

5.5 Artificial Intelligence and Intelligent CAPP

AI is making its way into CAPP to help with decisions made by skilled process planners. Rojek (2017) explored the neural-network based approaches to technological process planning and Kumar (2017) mentions expert system, neural network and evolutionary approaches as important application of AI in manufacturing and CAPP. AI, machine learning and data analytics can help CAPP systems learn from past production data and expert knowledge to adapt to future process plans.

This will allow increased adaptability to changes in machine, materials, resources, and production requirements (Besharati-Foumani, Lohtander and Varis, 2019). This caution is justified by the experience gained in the use of AI for adjacent planning functions. Senda et al. (2026) created a random forest model to correlate decisions made when conducting boiler maintenance with reliability, availability and cost at a thermal power station and found that the value of the model would not be realised without the capability to feed the results into the computerised maintenance management system and work-order process. Mashava et al. (2026) selected interpretable rule-based inference as their method, as they had limited labelled fault data. Similarly, by analogy, value can be added to AI process plans only if the plans are linked to enterprise systems and if their reasoning can be validated by planners. But intelligent CAPP is not enough to overcome the integration problem.

There is still a need, generated by AI, to communicate these process plans to ERP and MRP systems in a way that these systems can interpret and use. Manufacturing environments are also dynamic, so that human planners may still be needed for validation or modification of automatically-generated plans. Cognitive overload, fatigue, and interface design and training are cognitive factors that influence safe and effective work in manufacturing in Zimbabwe (Muhla et al., 2025b) and these factors also play a role in the interactions between planners and automated planning tools. The trends in the current developments indicate that human-AI collaboration and adaptive planning are still expected in the future, not the replacement of the human expertise.

5.6 Benefits and Challenges of CAPP–ERP–MRP Integration

By facilitating direct data sharing, CAPP–ERP–MRP integration can enhance the consistency of data, minimize errors and duplication, and boost the responsiveness of planning. Interoperability and data quality are important issues that need attention: different systems may store data in different formats and with different terminology (Seeharit, Šormaz and Fuloria, 2025).

Splintering errors across systems can also be caused by poor CAPP data. ERP can incorporate dedicated scheduling tools, while MRP can often be based on assumptions with respect to the availability of capacity and lead time, resulting in decreased performance when it comes to uncertainty (Thevenin and Adulyasak, 2021; Schlenkrich et al., 2024). T

he limitations are starting to be addressed by the closer coupling of planning levels, respectively in the fields of smart production planning and control, as well as in the field of integrated process planning and scheduling, as reflected in the corresponding reviews (Wagner et al., 2020; Varela et al., 2021). Management support and communication and organisational readiness are also important to successful integration (Ali and Miller, 2017).

These barriers are exacerbated in developing economies – Zimbabwean manufacturers report high cost of Industry 4.0 solutions, lack of a digital strategy, low level of government incentives and fear of cyber-attacks (Muhla et al., 2025a); while human-centred interventions are hindered by low level of management support, awareness and training (Muhla et al., 2025b).

6 RESEARCH GAPS AND FUTURE DIRECTIONS

6.1 Research Gap

The research on CAPP, MRP and ERP has been substantial and there is growing interest in integrating these two. CAPP has moved from the variant and generative approach to intelligent and AI-supported process planning, and ERP and MRP have evolved toward increasingly wide integration of the entire production process, materials information, and enterprise information. But the evidence is still disorganized. CAPP research is mainly related to process plan generation, ERP related to enterprise integration and MRP related to material requirements and production planning. While some articles like Jaskó et al. (2020) and Seeharit, Šormaz and Fuloria (2025) illustrate the possible integration paths, there is still limited evidence in practical manufacturing environments on the end-to-end integration of process information generated by CAPP to MRP and ERP. There are three areas of particular note.

The interoperability is first a problem due to the use of different data structures and semantic models. Secondly, there is limited empirical data to measure if integration saves planning time, increases data accuracy, increases scheduling,

increases inventory management or increases production responsiveness. Thirdly, the use of AI-powered CAPP with ERP/MRP is still under-researched. Hence, more systematic research is needed to understand the possible ways of integrating CAPP with MRP/ERP, the appropriate technology and architecture for such integration, the proven benefits, and the technology and organisational issues to be addressed. Therefore, further systematic investigation is required to establish how CAPP can be integrated with MRP and ERP, which technologies and architectures support such integration, what benefits have been demonstrated, and what technical and organisational challenges remain.

6.2 Future Directions

Digital twin-enabled closed-loop planning – Extend digital twin-based CAPP to enable bidirectional data exchange with ERP and MRP, allowing real-time capacity and material constraints to influence process-plan generation (Afif and Sarhan, 2025).

Ontology-driven interoperability – Develop shared, standards-based ontologies to enable seamless data exchange between CAPP, ERP, MRP and MES without bespoke interfaces

(Panetto, Dassisti and Tursi, 2012; Jaskó et al., 2020; Seeharit, Šormaz and Fuloria, 2025).

AI-driven and generative CAPP – Integrate generative CAPP with organisational ERP/MRP data so that automatically generated process plans reflect existing resource and material constraints.

Uncertainty-aware MRP – Apply stochastic and rolling-horizon optimisation to account for finite capacity and uncertainty, using realistic CAPP-generated process plans (Schlenkrich et al., 2024).

SME-oriented integration – Develop affordable cloud-based and low-code CAPP-ERP/MRP solutions tailored to the needs and constraints of SMEs, drawing on evidence that functional systems can be built from low-cost, locally maintainable components (Munotyaani et al., 2026; Mashava et al., 2026).

Empirical multi-case validation – Conduct larger, multi-industry studies to measure integration benefits through lead time, planning accuracy, schedule adherence and resource utilisation.

Energy- and sustainability-aware planning – Carry energy and cycle-time data from validated process parameters into ERP costing and MRP lead times, so that process plans can be selected on cost, energy and quality together (Tayisepi et al., 2023; Tayisepi et al., 2024; Ghobakhloo, 2020).

Learning factories as integration testbeds – Use learning factories to prototype and teach CAPP-ERP/MRP integration in realistic production settings, which would also address the skills gaps reported in Southern African engineering education (Ndiyamba et al., 2026).

7 CONCLUSION

Process planning, enterprise integration and material planning can be facilitated by CAPP, ERP and MRP; their integration can lead to data consistency, responsiveness and coordination in the enterprise. It is observed that literature in general follows a clear trend from data exchange based on STEP, to service-oriented, ontology-based and digital-twin-enabled integration. However, there are some restrictions on data quality, semantic interoperability, ERP implementation and MRP awareness of capacity. Existing research is largely conceptual and single case oriented while the applications of SMEs and developing economies and the cross-industry applications are receiving very little attention, where cost, strategy, and skills are limiting factors. Future research should therefore consider digital twins, interoperability, uncertainty-aware and energy-aware planning, and wider empirical validation and should make use of learning factories and low-cost reference architectures to enable integration to be realised beyond the size of large enterprises.

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] Afif, M.F. and Sarhan, A.A.D. (2025) 'Computer-aided process planning, digital twin, and smart manufacturing: interconnections and integration in CNC machining processes', *International Journal of Production Research*, 63(24), pp. 9593–9632. Available at: <https://doi.org/10.1080/00207543.2025.2521717>.
- [2] Aivaliotis, P., Georgoulas, K. and Chrysosouris, G. (2019) 'The use of digital twin for predictive maintenance in manufacturing', *International Journal of Computer Integrated Manufacturing*, 32(11), pp. 1067–1080.
- [3] Al-wswasi, M., Ivanov, A. and Makatsoris, H. (2018) 'A survey on smart automated computer-aided process planning (ACAPP) techniques', *The International Journal of Advanced Manufacturing Technology*, 97, pp. 809–832. Available at: <https://doi.org/10.1007/s00170-018-1966-1>.
- [4] Ali, M. and Miller, L. (2017) 'ERP system implementation in large enterprises – a systematic literature review', *Journal of Enterprise Information Management*, 30(4), pp. 666–692.
- [5] Balaha, F., Albinali, H., Alrabiah, H., Ali, M. and Bahroun, Z. (2025) 'Leveraging ERP systems for smart manufacturing: a review of integration practices in the Industry 4.0 era', *Proceedings of the International Conference on Computers and Industrial Engineering*, pp. 227–236.
- [6] Besharati-Foumani, H., Lohtander, M. and Varis, J. (2019) 'Intelligent process planning for smart manufacturing systems: a state-of-the-art review', *Procedia Manufacturing*, 38, pp. 156–162. Available at: <https://doi.org/10.1016/j.promfg.2020.01.021>.
- [7] Burggräf, P., Adlon, T. and Schäfer, N. (2024) 'Towards digital-twin-driven factory planning – a systematic review', *Procedia CIRP*, 126, pp. 248–253.
- [8] Cieply, J., Disselkamp, J.-P., Dyck, F., Alturk, W., Kühn, A. and Dumitrescu, R. (2023) 'A systematic literature review on the digital twin of the factory in the context of the product and factory lifecycle', *Procedia CIRP*, 119, pp. 834–840.
- [9] Fede, G., Sgarbossa, F. and Paltrinieri, N. (2024) 'Integrating production and maintenance planning in process industries using digital twin: a literature review', *IFAC-PapersOnLine*, 58(19), pp. 151–156.
- [10] Ferrari, A.M., Volpi, L., Settembre-Blundo, D. and García-Muiña, F.E. (2020) 'Dynamic life cycle assessment integrating life cycle inventory and Enterprise Resource Planning in an Industry 4.0 environment', *Journal of Cleaner Production*, 286, 125314.
- [11] Ford, M. (2018) 'Architectures and interoperability for smart manufacturing', *Procedia Manufacturing*, 26, pp. 54–61.
- [12] Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019) 'Industry 4.0 technologies: implementation patterns in manufacturing companies', *International Journal of Production Economics*, 210, pp. 15–26.
- [13] Ghobakhloo, M. (2020) 'Industry 4.0, digitization, and opportunities for sustainability', *Journal of Cleaner Production*, 252, 119869.
- [14] Hedberg, T., Lubell, J., Fischer, L., Maggiano, L. and Feeney, A.B. (2016) 'Testing the digital thread in support of model-based manufacturing and inspection', *Journal of Computing and Information Science in Engineering*, 16(2).
- [15] Hermann, M., Pentek, T. and Otto, B. (2016) 'Design principles for Industrie 4.0 scenarios', in *2016 49th Hawaii International Conference on System Sciences (HICSS)*. IEEE, pp. 3928–3937.
- [16] 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. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0051>.
- [17] Jaskó, S., Skrop, A., Holczinger, T., Chován, T. and Abonyi, J. (2020) 'Development of manufacturing execution systems in accordance with Industry 4.0 requirements: a review of standard- and ontology-based methodologies and tools', *Computers in Industry*, 123, 103300. Available at: <https://doi.org/10.1016/j.compind.2020.103300>.
- [18] Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020) 'Characterising the digital twin: a systematic literature review', *CIRP Journal of Manufacturing Science and Technology*, 29, pp. 36–52.
- [19] Kiran, D.R. (2019) *Production planning and control: a comprehensive approach*. Oxford: Butterworth-Heinemann.
- [20] 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.
- [21] Kumar, S.P.L. (2017) 'State of the art-intense review on artificial intelligence systems application in process planning and manufacturing', *Engineering Applications of Artificial Intelligence*, 65, pp. 294–329.

- [22] Kutin, A., Dolgov, V., Sedykh, M. and Ivashin, S. (2018) 'Integration of different computer-aided systems in product designing and process planning on digital manufacturing', *Procedia CIRP*, 67, pp. 476–481.
- [23] Liao, Y., Deschamps, F., Loures, E.F.R. and Ramos, L.F.P. (2017) 'Past, present and future of Industry 4.0 – a systematic literature review and research agenda proposal', *International Journal of Production Research*, 55(12), pp. 3609–3629.
- [24] Liu, S., Bao, J. and Zheng, P. (2023) 'A review of digital twin-driven machining: from digitization to intellectualization', *Journal of Manufacturing Systems*, 67, pp. 361–378.
- [25] Lu, Y., Morris, K.C. and Frechette, S. (2016) *Current standards landscape for smart manufacturing systems*. NISTIR 8107. Gaithersburg, MD: National Institute of Standards and Technology.
- [26] 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. Available at: <https://doi.org/10.30574/wjaets.2026.20.2.0419>.
- [27] Mapindu, I., Munhuwamambo, G., Mashava, D. and Ngwenya, L. (2026b) 'Optimization of cutting parameters in CNC milling using the Taguchi method', *Global Journal of Engineering and Technology Advances*, 28(2), pp. 149–162. Available at: <https://doi.org/10.30574/gjeta.2026.28.2.0223>.
- [28] Mapindu, I., Muhla, T.M., Chinguwo, K.N. and Foya, A. (2026c) 'Process parameter optimization for 3D printing using the Taguchi method', *Open Access Research Journal of Science and Technology*, 18(1), pp. 34–45. Available at: <https://doi.org/10.53022/oarjst.2026.18.1.0082>.
- [29] 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>
- [30] 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. Available at: <https://doi.org/10.53022/oarjst.2026.17.2.0071>.
- [31] Mies, D., Marsden, W. and Warde, S. (2016) 'Overview of additive manufacturing informatics: a digital thread', *Integrating Materials and Manufacturing Innovation*, 5, pp. 114–142.
- [32] 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.
- [33] Muhla, T.M., Mashava, D., Kanyemba, G., Mapindu, I. and Goriwondo, W.M. (2025a) '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. Available at: <https://doi.org/10.30574/wjaets.2025.15.2.0653>.
- [34] Muhla, T., Kanyemba, G., Mapindu, I., Chinguwo, N., Mashava, D. and Goriwondo, W. (2025b) '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. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0037>.
- [35] Munotyani, 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. Available at: <https://doi.org/10.32497/jrm.v21i1.6954>.
- [36] 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. Available at: <https://doi.org/10.30574/gjeta.2025.23.3.0166>.
- [37] Najy, R.J. (2020) 'MRP (material requirement planning) applications in industry – a review', *IJRDO – Journal of Business Management*, 6(2), pp. 1–13.
- [38] 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 *CLF 2026 Book of Short Papers on Learning Factories: Proceedings of the 16th Conference on Learning Factories*, Bolzano, Italy, 5–7 May 2026. Bolzano: Free University of Bozen-Bolzano, pp. 93–99. Available at: <https://doi.org/10.5281/zenodo.20780648>.
- [39] Okpala, C.C. and Okonkwo, A.K. (2018) 'Computer aided process planning in manufacturing: a review', *International Journal of Advanced Engineering and Technology*, 2(2), pp. 49–54.
- [40] Ouahabi, N., Chebak, A., Kamach, O., Laayati, O. and Zegrari, M. (2024) 'Leveraging digital twin into dynamic production scheduling: a review', *Robotics and Computer-Integrated Manufacturing*, 89, 102778.

- [41] 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. Available at: <https://doi.org/10.1136/bmj.n71>.
- [42] Panetto, H., Dassisti, M. and Tursi, A. (2012) 'ONTO-PDM: product-driven ontology for product data management interoperability within manufacturing process environment', *Advanced Engineering Informatics*, 26(2), pp. 334–348. Available at: <https://doi.org/10.1016/j.aei.2011.12.002>.
- [43] Pereira, A.C. and Romero, F. (2017) 'A review of the meanings and the implications of the Industry 4.0 concept', *Procedia Manufacturing*, 13, pp. 1206–1214.
- [44] Qin, J., Liu, Y. and Grosvenor, R. (2016) 'A categorical framework of manufacturing for Industry 4.0 and beyond', *Procedia CIRP*, 52, pp. 173–178.
- [45] Raheem, A., De Marchi, M. and Dallasega, P. (2025) 'Digital twin driven factory and production planning (FPP)', *Production & Manufacturing Research*, 13(1).
- [46] Rojek, I. (2017) 'Technological process planning by the use of neural networks', *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 31(1), pp. 1–15. Available at: <https://doi.org/10.1017/S0890060416000147>.
- [47] Schlenkrich, M., Seiringer, W., Altendorfer, K. and Parragh, S.N. (2024) 'Enhancing rolling horizon production planning through stochastic optimization evaluated by means of simulation', *arXiv preprint*, arXiv:2402.14506. Available at: <https://doi.org/10.48550/arXiv.2402.14506>.
- [48] Seeharit, S., Šormaz, D.N. and Fuloria, M.M. (2025) 'Interoperability between ERP and PLM systems using ontologies – a case study', in Šormaz, D.N., Bidanda, B., Alhawari, O. and Geng, Z. (eds) *Intelligent production and Industry 5.0 with human touch, resilience, and circular economy*. Cham: Springer, pp. 515–527. Available at: https://doi.org/10.1007/978-3-031-77723-3_47.
- [49] Seipolt, A., Buschermöhle, R. and Hasselbring, W. (2025) 'Digital twins in manufacturing: a systematic literature review with retrieval-augmented generation', *IEEE Access*, 13, pp. 172562–172583.
- [50] 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. Available at: <https://doi.org/10.53022/oarjst.2026.17.2.0070>.
- [51] Shao, G. (2024) 'Manufacturing digital twin standards', paper presented at the *2024 International Conference on Engineering Digital Twins*, Linz, Austria.
- [52] Shao, G. and Helu, M. (2020) 'Framework for a digital twin in manufacturing: scope and requirements', *Manufacturing Letters*, 24, pp. 64–67.
- [53] Shao, G., Kibira, D. and Frechette, S. (2024) 'Digital twins for advanced manufacturing: the standardized approach', in *Digital twins, simulation, and the metaverse*. Cham: Springer.
- [54] Shojaeinasab, A., Charter, T., Jalayer, M., Khadivi, M., Ogunfowora, O., Raiyani, N., Yaghoubi, M. and Najjaran, H. (2022) 'Intelligent manufacturing execution systems: a systematic review', *Journal of Manufacturing Systems*, 62, pp. 503–522.
- [55] Sony, M. (2020) 'Pros and cons of implementing Industry 4.0 for the organizations: a review and synthesis of evidence', *Production & Manufacturing Research*, 8(1), pp. 244–272.
- [56] Sony, M. and Naik, S. (2020) 'Industry 4.0 integration with socio-technical systems theory: a systematic review and proposed theoretical model', *Technology in Society*, 61, 101248.
- [57] Soori, M., Arezoo, B. and Dastres, R. (2023) 'Digital twin for smart manufacturing: a review', *Sustainable Manufacturing and Service Economics*, 2, 100017.
- [58] Soori, M. and Asmael, M. (2021) 'Classification of research and applications of the computer aided process planning in manufacturing systems', *Independent Journal of Management & Production*, 12(5).
- [59] Tandi, 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. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0050>.
- [60] Tao, F., Qi, Q., Liu, A. and Kusiak, A. (2018) 'Data-driven smart manufacturing', *Journal of Manufacturing Systems*, 48, pp. 157–169.
- [61] Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2019) 'Digital twin in industry: state-of-the-art', *IEEE Transactions on Industrial Informatics*, 15(4), pp. 2405–2415.

- [62] 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. Available at: <https://doi.org/10.9734/JERR/2023/v25i111023>.
- [63] 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. Available at: <https://doi.org/10.22115/cepm.2024.473138.1324>.
- [64] Thevenin, S. and Adulyasak, Y. (2021) 'Material requirements planning under demand uncertainty using stochastic optimization', *Production and Operations Management*, 30(2), pp. 475–493.
- [65] Tortorella, G.L. and Fettermann, D. (2018) 'Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies', *International Journal of Production Research*, 56(8), pp. 2975–2987.
- [66] Varela, M.L.R., Putnik, G.D., Manupati, V.K., Rajyalakshmi, G., Trojanowska, J. and Machado, J. (2021) 'Integrated process planning and scheduling in networked manufacturing systems for I4.0: a review and framework proposal', *Wireless Networks*, 27, pp. 1587–1599.
- [67] Wagner, T., Walton, R., Toma, M. and Simoes, C. (2020) 'Smart production planning and control in the Industry 4.0 context: a systematic literature review', *Computers & Industrial Engineering*, 149, 106774.
- [68] Weyer, S., Schmitt, M., Ohmer, M. and Gorecky, D. (2015) 'Towards Industry 4.0 – standardization as the crucial challenge for highly modular, multi-vendor production systems', *IFAC-PapersOnLine*, 48(3), pp. 579–584.
- [69] Wooley, A., Silva, D.F. and Bitencourt, J. (2023) 'When is a simulation a digital twin? A systematic literature review', *Manufacturing Letters*, 35, pp. 940–951.
- [70] Xiao, Y., Zheng, S., Shi, J., Du, X. and Hong, J. (2023) 'Knowledge graph-based manufacturing process planning: a state-of-the-art review', *Journal of Manufacturing Systems*, 70, pp. 417–435.
- [71] 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.
- [72] Yao, J.-F., Yang, Y., Wang, X.-C. and Zhang, X.-P. (2023) 'Systematic review of digital twin technology and applications', *Visual Computing for Industry, Biomedicine, and Art*, 6, 10.
- [73] 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.
- [74] Zhou, J. and Camba, J.D. (2021) 'Computer-aided process planning in immersive environments: a critical review', *Computers in Industry*, 133, 103547.