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Integrating Digital Twins with CAD, CAE and CAM in the Design and Manufacture of Garment Industry Equipment for Green Manufacturing: A Proposed Framework for Small and Medium-Sized Enterprises

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ABSTRACT:

Objective: Green manufacturing requires resource and energy targets to be considered from the equipment design stage. In textiles and garments, digital twin research has focused mainly on the management, simulation, optimization and maintenance of production lines; combining digital twins with computer-aided design, engineering and manufacturing (CAD, CAE, CAM) to design and manufacture mechanical equipment for the garment industry has not been clarified, particularly for small and medium-sized enterprises (SMEs) in Vietnam. **Methodology:** A structured review combined with qualitative content analysis was carried out on 26 peer-reviewed works published between 2017 and 2026, and the Technology, Organization, Environment (TOE) framework was used to interpret implementation conditions.

Findings: The result is a three-tier integrated framework with three research propositions: (P1) virtual testing improves resource efficiency by reducing physical test loops, prototypes, test blanks and scrap; (P2) simultaneous optimization of the mechanical structure, electric drive and control, combined with operational data feedback, improves energy efficiency and the equipment life cycle; (P3) the extent to which digital capability is converted into green value depends on the technological, organizational and environmental conditions of the enterprise. **Significance:** The paper proposes a three-phase implementation roadmap for SMEs that manufacture jigs, sewing guides, spare parts and special-purpose mechanism assemblies for the garment industry, and identifies managerial issues concerning cost, human resources, data ownership and the servitization business model.

KEYWORDS: digital twin, CAD, CAE, CAM, garment industry equipment, green manufacturing, small and medium-sized enterprises, TOE framework

INTRODUCTION

The need to reduce material consumption, energy consumption and emissions has become a core element of sustainable manufacturing strategy. Green manufacturing therefore has to be addressed from the design and development of products and equipment, not only at the operation stage. Bendig et al. (2023) show that green manufacturing is made up of groups of factors relating to technology, processes and environmental outcomes, among which resource efficiency plays the central role. Along these lines, digital design and simulation technologies allow part of the testing, evaluation and optimization work to be moved from the physical environment to the digital environment.

The digital twin is a representative technology of this transition. Unlike a static digital model, a digital twin maintains a data link between the physical object and the digital model, and thereby supports simulation, monitoring, analysis and feedback across the design, manufacturing and use stages; He and Bai (2021) confirmed this role in sustainable intelligent manufacturing. The digital twin is most effective when combined with three tools: Computer-Aided Design (CAD), Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM), hereafter referred to collectively as the CAD/CAE/CAM system. This combination makes it possible to increase virtual testing, optimize design alternatives and limit unnecessary physical test loops.

In the garment industry, the digital twin has only recently begun to be studied and deployed. Alam et al. (2023) developed a digital twin framework for a sewing line, focusing on dynamic simulation, bottleneck removal, downtime reduction and higher production efficiency. Bi et al. (2025) observe that digital twin research in apparel production is still at an early stage and mainly serves the management, optimization and maintenance of production lines. Angelova (2025) shows that digital twin applications in the textile industry remain fragmented and that many application domains are still unexplored.

In Vietnam, this issue concerns a specific group of enterprises. Textiles and garments are a key export sector, with export turnover in 2025 estimated at about USD 46 billion (VCCI, 2025), yet industrial sewing machines are mainly imported from China, Japan and Taiwan (China), with China accounting for the largest share (Thế Vinh, 2021). The domestic mechanical engineering sector has about 25,000 enterprises but meets only nearly one third of domestic demand for mechanical products (Ministry of Industry and Trade, 2022). Enterprises that design and manufacture garment industry equipment are therefore mechanical engineering firms, most of them small and medium-sized, which design and manufacture jigs, sewing guides, templates, spare parts and special-purpose mechanism assemblies, or which upgrade and partly automate imported equipment for garment

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factories. Hoàng Xuân Hiệp et al. (2026) show that a domestically designed and manufactured semi-automatic guide, jig and template system for a programmable sewing machine reduced cycle time by 30.3% and increased output by 43.5% in the pocket-facing sewing operation; this is the type of product at which the proposed framework is aimed. These enterprises face the barriers common to SMEs in digital transformation: 60.1% of surveyed enterprises considered the cost of investing in and applying digital technology to be the greatest difficulty, alongside difficulties in changing business habits and a shortage of in-house human resources (Agency for Enterprise Development and USAID LinkSME, 2021). The capability to build digital twins of machine tools has begun to take shape in domestic training institutions (Phạm Văn Đông, 2024), but it has not yet been connected with the design and manufacture of garment industry equipment.

Against this background, the paper addresses the gap concerning the integration of digital twins with the CAD/CAE/CAM system in the design and manufacture of garment industry equipment for green manufacturing, and the conditions under which SMEs can implement this integration. Two mechanisms are examined: improving resource efficiency in the development and manufacturing stage, and improving energy efficiency and life-cycle efficiency in the equipment use stage. On the basis of a synthesis of secondary data and the TOE theoretical framework, the paper proposes an analytical framework in the form of testable research propositions and draws managerial implications for SMEs that design and manufacture garment industry equipment.

LITERATURE REVIEW

Digital twins in the design and development of manufacturing systems

The digital twin is a foundational technology of manufacturing digitalization that maintains data exchange between the physical space and the digital space. Kritzinger et al. (2018) distinguish three levels of integration: the digital model (no automated data exchange), the digital shadow (data flow automatically in one direction, from the physical object to the model) and the digital twin (data are exchanged automatically in both directions). In design and production engineering, Schleich et al. (2017) emphasize the possibility of narrowing the gap between design and manufacturing through a virtual product model that also reflects the geometric deviations arising in machining and assembly. From a life-cycle perspective, Tao et al. (2018) extend the digital twin to the design, manufacturing and service stages; Qi and Tao (2018) confirm its ability to provide support from design through to operation and maintenance; Lo et al. (2021) summarize the functions of monitoring, simulation, optimization and failure prediction in product development. For electromechanical products, Cui et al. (2023) show that the application focus changes with the stage: modeling during design, support for process planning during manufacturing, and control and health management during operation. The digital twin is thus a data-linking layer running through the whole product life cycle and the basis for integration with the CAD/CAE/CAM system.

CAD, CAE, CAM and virtual engineering

In mechanical product development, CAD builds the three-dimensional geometric model and the engineering data; CAE verifies the strength, stiffness, dynamics and vibration of the structure before manufacturing; CAM converts design data into process plans and programs for numerically controlled machine tools. The digital twin extends this system by tying the digital model to the actual state of the physical object (Schleich et al., 2017; Lo et al., 2021), providing the foundation for virtual engineering, which comprises virtual prototyping, virtual testing and virtual commissioning, that is, checking and tuning the control program and the working sequence of the machine on the digital model before installation. Ugarte et al. (2022) integrated the digital twin with CAD and CAM data and the automation system for the virtual commissioning of machine tools; Wang et al. (2023) and Sun et al. (2024) used digital twins and scenario simulation to tune the system before the machine was put into operation. These results show that CAD, CAE, CAM and the digital twin can form a continuous data chain and thereby replace part of the physical test loops.

Green manufacturing and sustainable design

Green manufacturing aims to reduce environmental impact through the efficient use of materials and energy and the limitation of waste throughout the product life cycle, and covers solutions in design, processes and resource management (Bendig et al., 2023). Ahmad et al. (2018) call for environmental impact to be considered from the earliest steps of product development; Kishawy et al. (2018) propose that objectives concerning materials, energy and manufacturability be built into design decisions. For mechanical equipment, choices of structure, material, drive solution and machining process directly affect blank mass, the scrap rate and energy consumption during both manufacturing and operation. Rojek et al. (2021) show that the digital twin enables real-world data to be fed back to the design stage; for machining specifically, Fernando et al. (2021) identify the reduction of energy and metalworking fluid consumption as the two main directions. Accordingly, four environmental outcomes are selected for the analytical framework: material efficiency, waste reduction, energy efficiency and extension of the equipment life cycle.

Digital twins and digital transformation in textiles and garments

Glogar et al. (2025) show that computer-aided design, three-dimensional simulation, artificial intelligence and the Internet of Things are increasingly integrated into the sustainable design and production of textiles and clothing; Hassan et al. (2025) point out the role of digital technologies in the circular economy of the textile industry. The digital twin has already been applied directly to apparel production: the framework of Alam et al. (2023) was validated on a real sewing line, using real-time data and dynamic simulation to identify bottlenecks and reduce downtime. However, this line of research is still at an early stage and mainly serves the management, optimization and maintenance of production lines (Bi et al., 2025); applications in the textile industry remain fragmented (Angelova, 2025), and the level of adoption of digital technology differs considerably between operations and between enterprises (Islam et al., 2026). Ianniello et al. (2026) identify resource efficiency, waste reduction and traceability as the environmental outcomes most often associated with technologies in the sector. The integration of digital twins with the CAD/CAE/CAM system to design and manufacture the mechanical equipment of the garment industry itself, with the aim of reducing material consumption, waste and energy, has thus not been clarified. This is the gap that the paper addresses.

Management theory foundations: the TOE framework and the dynamic capabilities view

The research streams above mainly explain technical mechanisms; they do not explain why enterprises decide to adopt a technology and how they convert technology into capability. The paper uses two complementary lenses. First, the Technology, Organization, Environment (TOE) framework

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of Tornatzky and Fleischer (1990) holds that the decision to adopt a technological innovation is influenced by three groups of conditions: the technological context (the characteristics, compatibility and cost of the technology and the available infrastructure), the organizational context (size, financial resources, human resources, leadership commitment) and the environmental context (customers, partners, solution providers, support policies). This framework suits SMEs because the barriers of cost, human resources and data scale can all be placed in these three groups. Second, the dynamic capabilities view (Teece et al., 1997) holds that advantage does not come from owning resources but from the ability to integrate, build and reconfigure resources in response to changes in the environment. Through this lens, CAD, CAE, CAM and the digital twin are only resources; green value is formed when the enterprise builds the capability to integrate data and to learn from operational data. The two lenses are used to interpret the first tier of the framework, to formulate proposition P3 (see the subsection *Integrated framework for green manufacturing* in Results) and to analyze implementation conditions (see the subsection *Implementation conditions for small and medium-sized enterprises*).

MATERIALS AND METHODS

The study uses a structured review combined with qualitative content analysis of secondary data; it does not use primary survey or experimental data and does not follow a full systematic review protocol. The procedure consists of four steps.

Step 1. Literature search. The sources are peer-reviewed scientific papers published in journals and proceedings indexed in international academic databases between 2017 and 2026. The search was carried out with five groups of keywords (Table 1), using the corresponding international terms.

Step 2. Screening. A document was selected when it met three criteria simultaneously: (i) it relates directly to at least one component of the research framework; (ii) it has complete, verifiable bibliographic information; (iii) it provides evidence that can be used to reason about the technology, the impact mechanism or the environmental outcome. Commercial promotional material, sources of unclear origin, and content that was duplicated or not directly related to design, manufacturing and sustainability were excluded. After screening, 26 works were included in the analysis (Appendix 1).

Step 3. Coding. Each document was coded against five criteria: technology, life-cycle stage, application object, impact mechanism and green manufacturing outcome. The coding result for each work is presented in Appendix 1 so that readers can verify the basis of Table 2 and Figure 1.

Step 4. Synthesis. The evidence was sorted into five groups (Table 1) and then cross-compared between groups to identify the research gap, propose the research propositions and build the integrated framework. Because a qualitative review does not allow causal relationships to be established, the propositions (P1, P2, P3) are presented as hypotheses that can be tested through case studies or experiments. The results are presented under four headings: the integration architecture; the two green value-creation pathways; the proposed integrated framework; and the implementation conditions and business model implications for SMEs. In addition to the 26 works in the coded data set, the paper draws on a number of further sources on management theory, business models, the industry context in Vietnam and sewing machine drive systems in order to interpret the results; these sources did not take part in the coding process.

Table 1. Framework for collecting and classifying the literature used in the study

Evidence group	Main content analyzed	Typical search keywords	Role in the study
Digital twins and product development	Design, simulation, data feedback, product life cycle	digital twin, product design, product development, manufacturing	Establishes the theoretical foundation of the digital twin
CAD, CAE, CAM and virtual engineering	CAD, CAE, CAM; virtual prototyping, virtual testing, virtual commissioning	computer-aided design and manufacturing, virtual prototyping, virtual testing, virtual commissioning	Explains the technical mechanism
Digital twins and sustainable manufacturing	Resources, energy, waste, life cycle	sustainable manufacturing, green manufacturing, waste reduction	Identifies the environmental outcomes
Digital transformation in textiles and garments	Application of digital twins and digital technologies in textile and garment production	textile, apparel, garment manufacturing, garment industry equipment	Identifies the context and the gap in the sector
Eco-design, resource and energy efficiency	Sustainable design, materials, machining, energy, service life	eco-design, resource efficiency, energy efficiency, life cycle	Supports the reasoning on the two green value-creation pathways

Source: Compiled by the author.

RESULTS

Architecture for integrating digital twins with the CAD/CAE/CAM system in the development of garment industry equipment

The synthesis shows that the digital twin and the CAD/CAE/CAM system need to be organized as a continuous data chain in equipment development, consistent with the view of Tao et al. (2018). At the design stage, CAD and CAE data are the basis for building the digital model of the equipment in order to simulate the structure, motion, loads and expected operating modes; Lo et al. (2021) show that the digital twin extends the design model from geometric representation to the evaluation of behavior. For industrial sewing machines, fabric spreading machines and automatic fabric cutting machines, as well as the jigs, sewing guides and special-purpose mechanism assemblies fitted to these machines, this approach makes it possible to evaluate the structure, the actuating mechanisms, the drive system and the layout before manufacturing. At the

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process preparation and commissioning stage, the data are transferred to CAM and to the digital twin environment for virtual commissioning (Ugarte et al., 2022; Sun et al., 2024), so that shortcomings in the structure, motion or control sequence are detected early.

The data flow does not end at manufacturing. According to Cui et al. (2023), the operational data of electromechanical products continue to be used for health monitoring, control and product improvement. For garment industry equipment, real-world data on loads, vibration, electricity consumption, operating modes and failures can be fed back to the design model in order to develop the next generation of equipment. The chain made up of CAD, CAE, the digital twin, CAM, the physical equipment and operational data therefore forms a closed loop, which is the foundation for design optimization oriented towards green manufacturing.

Resource efficiency in design and manufacturing

The first mechanism is the reduction of the need for physical testing during equipment development. In the traditional mechanical design process, each adjustment to the structure, the transmission mechanism or the working parameters usually entails remaking the prototype, additional machining or the replacement of parts. When part of the evaluation work is moved to the digital environment, many alternatives are checked and discarded before any material is consumed. The quantitative evidence currently available comes mainly from machine tools. For the spindle system of a numerically controlled machine tool, the digital twin-based virtual commissioning method of Wang et al. (2023) shortened the response time by 13%, reduced the total system error by 54% and reduced commissioning time; the scenario simulation-based commissioning method of Sun et al. (2024) reduced the response time by about 12% and the steady-state error by about 52%, and shortened commissioning time. Ugarte et al. (2022) implemented virtual commissioning at a machine tool manufacturer but described the benefits mainly in qualitative terms and noted that these technologies are still little used in the machine tool industry. The above indicators measure the quality and duration of commissioning; they do not directly measure the number of prototypes, the blank mass or the material cost saved. The link from improved commissioning to resource savings therefore remains an inference that needs to be verified.

From the standpoint of sustainable design, decisions at the design stage govern the level of resource use over the whole product life cycle (Ahmad et al., 2018). If deviations in geometry, structure, assemblability or motion are detected early by simulation, the enterprise avoids manufacturing prototypes that fail, and thereby reduces metal blanks, the volume of machining and auxiliary supplies. Since energy and metalworking fluid are the two items to be controlled in sustainable machining (Fernando et al., 2021), reducing trial machining also indirectly reduces the consumption of cutting fluid and cutting tools; better material utilization and waste reduction are precisely the constituent components of green manufacturing (Bendig et al., 2023).

On the basis of the studies above, the first research proposition is put forward. *P1: The extent to which simulation, virtual testing and virtual commissioning are used in the development of garment industry equipment is positively related to resource efficiency, through the mediating mechanism of fewer physical test loops, prototypes and test blanks, which leads to less machined material, metal scrap and auxiliary supplies.* Direct quantitative data on garment industry equipment are still limited, so the proposition needs to be tested using indicators such as the number of test loops, the mass of test blanks and the scrap rate before and after adoption. Table 2 summarizes what is inherited from each research stream and the gap that remains.

Table 2. Summary of evidence streams and gaps relating to the research framework

Research stream	Established results	Relation to this study	Remaining gap
Digital twins and product development	Support simulation, optimization and data feedback across the life cycle	Foundation for design and virtual testing	Garment industry equipment is not addressed specifically
CAD, CAE, CAM and virtual engineering	Support design, analysis, process preparation for manufacturing and virtual commissioning	Can replace part of physical testing	The impact on resource efficiency in manufacturing garment industry equipment has not been clarified
Digital twins and sustainable manufacturing	Related to energy, resources, life cycle and maintenance	Basis for the two green value-creation pathways	Outcomes are usually considered separately
Digital twins in textiles and garments	Focus on simulation, line optimization, management and maintenance	Establishes the sector context	The design and manufacture of the mechanical equipment itself has received little study
Eco-design and sustainable machining	Emphasize materials, energy, waste and service life	Basis for defining green manufacturing outcomes	No link to digital twins and CAD/CAE/CAM in the garment industry

Source: Compiled by the author from Appendix 1.

Table 2 shows that the gap does not lie in the absence of any individual technology but in the fact that the digital twin, the CAD/CAE/CAM system, virtual engineering and environmental outcomes have not been linked in a single line of argument about the design and manufacture of garment industry equipment.

Design optimization, energy efficiency and the equipment life cycle

The digital twin combined with the CAD/CAE/CAM system also creates green value by raising design quality and the efficiency with which equipment is used: alternatives are compared and optimized in the digital environment before manufacturing, and Lim et al. (2020) show that the digital twin supports the design and optimization of engineering product families by exploiting data and digital models together.

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For mechanical equipment in the garment industry, design optimization can target the structure, the mass and moment of inertia of moving links, the balancing of mechanisms, the loads on the drive system and the working conditions of friction pairs. However, the electricity consumption of an industrial sewing machine depends first of all on the drive system and motor type, the standby mode and the way the machine is operated. A clutch motor consumes energy for the whole time the machine is switched on, whereas a servo motor consumes energy only according to sewing speed and sewing time and switches to standby when sewing stops; according to Nemeša (2023), a servo motor enables a sewing machine to use up to 70% less electricity than a clutch motor. Mechanical losses are therefore not the only decisive factor. Even so, in servo-driven equipment, the moment of inertia and the friction of the mechanism still, in principle, determine the required torque, the rated power of the motor and the energy consumed in each acceleration and deceleration, because a sewing machine works with a continuous start-stop cycle. The digital twin therefore needs to model the mechanical part, the electric drive and the control algorithm (speed profile, standby logic) together, instead of considering mechanical losses alone. Because direct evidence on garment industry equipment is still limited, the paper does not treat the relationship between design optimization and reduced energy consumption as deterministic; it regards it as a mechanism with a sound engineering basis that needs to be verified on each specific type of equipment.

From a life-cycle perspective, the digital twin supports sustainable product management by connecting design, manufacturing, operation and maintenance data (Rojek et al., 2021; Seegrün et al., 2023), with a contribution that runs through the whole system life cycle (Trienens et al., 2024); the research focus is also widening from productivity and operational efficiency to energy efficiency, material use and life-cycle efficiency (Omigbodun, 2026). For garment industry equipment, operational data on loads, vibration, electricity consumption, temperature and the condition of parts can be fed back to the digital model in order to adjust the design, plan maintenance and develop the next generation of equipment.

The second research proposition is put forward. *P2: Simulation and simultaneous optimization of the mechanical structure, electric drive and control, combined with the feedback of operational data to the design stage, are positively related to energy efficiency and equipment service life, through the mediating mechanism of a rational match between the motor, the motion profile and the standby mode, together with lower mechanical losses, vibration and wear.*

Integrated framework for green manufacturing

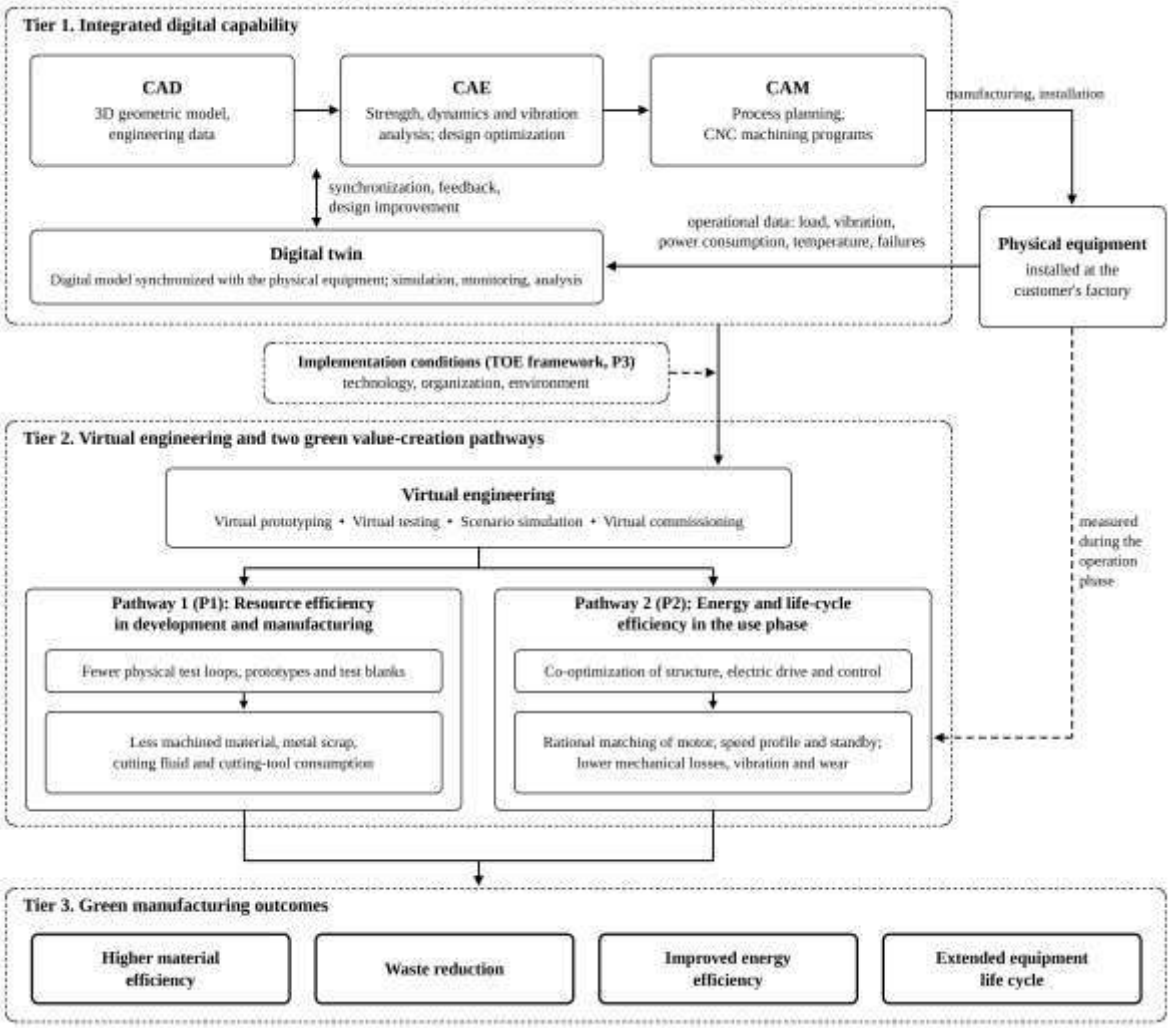

Figure 1. Framework for integrating digital twins with the CAD/CAE/CAM system in the design and manufacture of garment industry equipment for green manufacturing

Source: Proposed by the author on the basis of the literature synthesis.

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The proposed integrated framework (Figure 1) has three tiers. The first tier is integrated digital capability, comprising CAD, CAE, CAM and the digital twin: CAD and CAE build, analyze and optimize the alternatives; CAM prepares the process for manufacturing the physical equipment; the digital twin synchronizes the digital model with the physical equipment and receives operational data. The second tier is virtual engineering, comprising virtual prototyping, virtual testing, scenario simulation and virtual commissioning; from here the two green value-creation pathways corresponding to P1 and P2 are formed. The third tier consists of the four green manufacturing outcomes. The feedback loop in Figure 1 runs from the physical equipment in use at the customer's factory, through operational data, back to the digital twin and to CAD and CAE; this loop belongs to the use stage, so it is tied to the second pathway and is an input for the next generation of equipment.

The two pathways converge on four green manufacturing outcomes: higher material efficiency, waste reduction, improved energy efficiency and an extended equipment life cycle. Green value does not arise directly from owning the technology but from the way the technology is integrated into the cycle of design, simulation, manufacturing, operation and feedback. In line with the dynamic capabilities view, the third proposition is put forward. *P3: The relationships in P1 and P2 are stronger in enterprises with more favorable technological conditions (standardized design data, compatible software), organizational conditions (human resources for CAE and data analysis, leadership commitment) and environmental conditions (cooperation with customers, solution providers and training institutions).* In Figure 1, these conditions are shown as a factor moderating the conversion from the first tier to the second tier.

Implementation conditions for small and medium-sized enterprises

The benefits described above need to be set against costs, risks and barriers. At a general level, Fuller et al. (2020) identify the challenges of the digital twin as information technology infrastructure, data quality, privacy and security, the lack of standardization in modeling, and expectations about costs and benefits. Ianniello et al. (2026) record high implementation costs and difficulties with interoperability between systems as common negative effects of technologies in textiles and garments. Omigbodun (2026) notes that purely data-driven digital twins are often less accurate outside their training conditions and are difficult to validate. For SMEs, these barriers are compounded by small scale and by make-to-order, small-batch production. Table 3 classifies the implementation conditions according to the TOE framework and suggests ways of handling them.

Table 3. Implementation conditions and suggested responses for SMEs according to the TOE framework

Context	Main barriers and risks	Suggested responses
Technology	License costs for CAD, CAE and CAM and for computing hardware; the cost of building and calibrating models; requirements for sensors and measuring equipment; data compatibility between software packages; cybersecurity risks when equipment is connected	Start from the CAD and CAE already available; use subscription licenses or project-based computing services; fit sensors only for key parameters (electricity consumption, vibration); standardize data formats from the outset; apply access control and encrypt data transmission
Organization	Shortage of human resources for CAE, modeling and data analysis; small data scale due to make-to-order, small-batch production; limited capital; unclear leadership commitment	Train a core team; give priority to physics-based models combined with data over purely data-driven models; run a pilot project with measurable indicators before scaling up
Environment	Customers are reluctant to share operational data; dependence on solution providers; in-depth support for the digital transformation of SMEs is still limited	Data-sharing agreements with customers; outsourcing of services or cooperation with universities, research institutes and solution providers; use of support programs for the digital transformation of SMEs

Source: Compiled by the author from Tornatzky and Fleischer (1990), Fuller et al. (2020), Agency for Enterprise Development and USAID LinkSME (2021), Ianniello et al. (2026) and Omigbodun (2026).

From Table 3, a three-phase roadmap is proposed. Phase 1 (design digitalization): standardize CAD and CAE data and carry them over to CAM for a product group with a high order frequency, such as jigs and sewing guides; the indicators to be tracked are the number of times parts are remade and the mass of test blanks. Phase 2 (virtual engineering): apply virtual testing and virtual commissioning to mechanism assemblies with high prototype costs, where computing services may be hired or the work carried out jointly with a university. Phase 3 (operational digital twin): by agreement with the customer, fit sensors to a number of delivered machines to collect data on electricity consumption, vibration and failures for design improvement. This approach allows the enterprise to spread costs over time and to scale up only once the previous phase has demonstrated its benefits.

Business model implications: operational data and product servitization

The feedback loop in Figure 1 raises a managerial issue that technical analyses usually overlook: operational data are generated at the customer's factory and do not belong to the manufacturer. The enterprise therefore needs a clear agreement with the customer on ownership, the scope of sharing, the purpose of use and responsibility for data security; the data should be anonymized and collected only to the extent necessary for design improvement and maintenance. In return, these data open up the opportunity for product servitization, that is, moving from simply selling equipment to supplying equipment together with monitoring, maintenance and improvement services (Baines et al., 2009). Kohtamäki et al. (2019) classify digital servitization business models and stress that these models operate within an ecosystem of customers and partners and do not rely solely on the technological capability of the individual firm. For SMEs serving the garment industry, a feasible direction is to start with maintenance contracts that include the monitoring of electricity consumption and vibration for the mechanism assemblies already supplied, which both creates recurring revenue and provides data for testing P2.

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DISCUSSION

The novelty of the proposed framework does not lie in adding a technology but in reorganizing the relationships between technologies that have so far been studied separately. Building on Tao et al. (2018) and He and Bai (2021), the paper places the digital twin, CAD, CAE, CAM and virtual engineering in a single equipment development chain and ties this chain to environmental outcomes; the framework therefore does not claim that the digital twin in itself produces green manufacturing, but sets out the integration conditions and the mediating mechanisms. Compared with Alam et al. (2023) and Bi et al. (2025), who are concerned with the digital twin of the sewing line, the paper shifts the focus to the design and manufacture of the mechanical equipment of the garment industry itself, that is, it extends the scope of digital twin application from the level of production operation to the level of equipment development.

The paper makes three contributions. In terms of integration, the framework unifies research streams that have developed separately: life-cycle digital twins; CAD, CAE, CAM and virtual engineering; and digital transformation in textiles and garments. In terms of mechanisms, the two propositions P1 and P2 can be converted into specific measurement indicators; P2 places the electric drive and control alongside mechanical losses, in keeping with the energy consumption characteristics of sewing machines. In terms of management, the TOE framework and the dynamic capabilities view show that green value depends on implementation conditions (P3), while the data feedback loop ties the digital twin to the servitization business model; the framework thus becomes a tool that supports SMEs' decisions on investment, phased implementation and the design of customer relationships, and not merely a technical architecture.

CONCLUSION

Conclusions

On the basis of a structured review and content analysis of secondary data, the paper has analyzed the possibility of integrating digital twins with the CAD/CAE/CAM system in the design and manufacture of garment industry equipment for green manufacturing. The results show that the environmental value of the digital twin does not arise simply from digitalizing equipment; it depends on the degree of connection with CAD, CAE, CAM and operational data throughout the product development process, as well as on the technological, organizational and environmental conditions of the enterprise.

Three research propositions are put forward. First, simulation, virtual testing and virtual commissioning help to detect deviations before manufacturing and limit the number of physical test loops, prototypes and test blanks, and so have the potential to reduce machined material, metal scrap and auxiliary supplies. Second, simultaneous optimization of the mechanical structure, electric drive and control, combined with operational data feedback, contributes to lower electricity consumption, mechanical losses, vibration and wear, creating the conditions for higher energy efficiency and a longer equipment life cycle. Third, the extent to which digital capability is converted into green value depends on the conditions described by the TOE framework, which are a common weakness of SMEs.

Managerial implications for SMEs that design and manufacture garment industry equipment

First, digital transformation should be implemented in an integrated manner instead of through investment in separate software packages and technologies. Enterprises need to standardize CAD and CAE data and ensure that they can be carried over to CAM, simulation and the digital twin model. A continuous data flow avoids re-entry of data and the loss of information between departments, and makes it possible to use operational data to improve later generations of equipment.

Second, priority should be given to deploying the digital twin in those stages where physical testing is costly or where prototypes frequently have to be adjusted. Indicators such as the number of times parts are remade, the mass of test blanks, the scrap rate, the amount of cutting fluid consumed and commissioning time need to be tracked before and after virtual engineering is applied, so that the goal of green manufacturing is turned into measurable indicators.

Third, in the equipment use stage, data on loads, vibration, temperature, electricity consumption, working time and failures need to be collected step by step. These data serve not only maintenance; they need to be passed back to the design department in order to identify locations with large mechanical losses, rapid wear or excess strength, as well as motor selections and standby modes that are not yet appropriate, and thereby to improve the design towards rational material use, lower energy losses and longer equipment service life.

Fourth, SMEs should follow the three-phase roadmap set out in the subsection *Implementation conditions for small and medium-sized enterprises*, making use of outsourced services and cooperation with universities, research institutes and solution providers to reduce fixed costs; at the same time, they should establish data agreements with customers and consider the model of supplying equipment together with monitoring and maintenance services as a new direction for value creation (see the subsection *Business model implications: operational data and product servitization*).

Limitations and directions for further research

The study has three limitations. First, the proposed framework is built from secondary data, so propositions P1, P2 and P3 have not been tested with experimental data on garment industry equipment. Second, part of the evidence is drawn from research on machine tools, electromechanical products and smart manufacturing, so its applicability to each type of garment industry equipment needs to be assessed with caution. Third, the investment cost and economic efficiency of each phase of the proposed roadmap have not been quantified, and the Vietnamese context has so far been analyzed only from secondary data.

Further research needs to verify the proposed framework through case studies or experiments on a number of specific equipment groups, with measurement indicators including the number of physical test loops, the mass of material used, the amount of scrap, electricity consumption, the vibration level, the amount of wear and equipment service life, and to survey mechanical engineering SMEs serving the garment industry in order to test P3.

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