

PROCESS MINING-ENABLED DIGITAL TWINS: A SYSTEMATIC LITERATURE REVIEW OF TECHNIQUES, SIMULATION METHODS, AND SUPPLY CHAIN 5.0 IMPLICATIONS

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ABSTRACT

Digital Twins (DTs) enable real-time monitoring and adaptive decision-making, yet they are often developed through expert-driven approaches that only partially reflect real operations. Process Mining (PM) offers an alternative by extracting process knowledge from event logs, supporting DT creation, validation, and continuous updating. Despite growing interest, PM-DT research remains fragmented. This Systematic Literature Review (2020-2026) examines sectors adopting PM for DTs, the PM techniques used, and the modelling approaches combined with them. Results show the prevalence of generic frameworks, with manufacturing as the most mature field; Process Discovery is the dominating technique, while Conformance Checking is less explored. Discrete Event Simulation is the main modelling approach, complemented by Agent-Based Modelling, Petri Nets, and System Dynamics. The review also focuses on limited supply chain applications and frames PM-DT contributions in relation to the pillars of Supply Chain 5.0, highlighting directions for future research and practical development of data-driven PM-DT integrated systems.

INTRODUCTION

Digital Twins (DTs) are virtual replicas of physical systems that enable real-time monitoring, predictive analytics, and what-if scenario analysis, synchronizing operational data in real time (Tao et al., 2019). DTs represent a widespread paradigm since they were originally conceived for the aerospace and manufacturing industries, but have currently expanded across healthcare, logistics, and infrastructure, driven by Industry 4.0 adoption and advances in sensing technologies and data analytics (Kritzinger et al., 2018). A fundamental challenge faced by DTs is maintaining alignment between digital models and dynamic operational reality (Beerepoot et al., 2023). Traditional DT construction relies on manual process mapping,

expert interviews, and static documentation approaches, leaving three main limitations: they are labour-intensive, requiring significant expert effort for model construction and updates, they capture idealized or normative workflows rather than actual operational behaviours, missing the variations, exceptions, and workarounds that critically affect system performance, and become rapidly obsolete as operational conditions evolve, requiring costly manual updates to remain relevant (van der Aalst, 2016; Lugaresi & Matta, 2021a). Hence, continuous data-driven updates are needed to avoid risking that DTs disconnect from real systems (Bozorgi et al., 2020). Process Mining (PM) can address these limitations by accessing event data automatically recorded in operational information systems (e.g., ERP, MES, and WMS) to provide evidence-based model generation and continuous validation (van der Aalst, 2016): PM operate directly on event logs extracting process knowledge without requiring predefined models or assumptions and relying on three complementary capabilities that form the basis of adaptive DTs: (i) *Discovery*: automatically extracts “as-is” process models from event logs, enabling rapid generation of unbiased models based on operational reality. (ii) *Conformance checking*: Compares models with actual event data to identify deviations, quantify model accuracy, and detect anomalies, supporting both pre-implementation validation and runtime monitoring. (iii) *Enhancement*: enriches models with performance metrics, resource data and contextual information, allowing continuous adaptation (Overbeck et al., 2021). PM-DT integration also covers different simulation paradigms, like Discrete Event Simulation (DES) for operational, Petri Nets for formal verification of complex process logic, Agent-Based Modelling (ABM) for distributed autonomous systems, and System Dynamics (SD) for feedback loop analysis. Despite the theoretical benefits promised by the PM-DT integration, the literature remains fragmented across specific use cases in different sectors, like manufacturing (Lugaresi & Matta, 2021b), healthcare (Lay et al., 2022), logistics (Shams-Shemirani et al., 2024). In fact, current climate change, recent logistical crises, and the geopolitical situation have

highlighted the vulnerabilities of globally distributed networks (Ivanov & Dolgui, 2021). Hence, a transition toward Supply Chain 5.0 (SC5.0), a paradigm developing the technological bases typical of Industry 4.0 prioritizing human-centricity, resilience and sustainability, is required. Indeed, the core aspect of SC5.0 is represented by a holistic view of the decision-making processes: decisions are made considering the operational excellence for all the actors of the SC but also considers the 5.0 pillars as main drivers (Difrancesco & Klumpp, 2025). In this context, PM-DT integration serves as a strategic tool to support SC resilience, sustainability, and human-centricity across all sectors. Starting from these key points, this systematic literature review (SLR) is guided by three research questions: *RQ1*: Which sectors and application domains leverage PM for DT construction?; *RQ2*: Which PM techniques (discovery, conformance checking, enhancement) are employed in the DT lifecycle?; *RQ3*: Which simulation and modelling methods are combined with PM in DT implementations? Although PM and DT have each been individually reviewed in the literature, no prior systematic review has jointly mapped PM-DT integration across sectors, PM technique utilization, and simulation method adoption, nor linked these findings to the emerging SC5.0 paradigm. This review, therefore, fills a specific and unaddressed gap. The paper proceeds as follows: Section 2 details the SLR methodology; Section 3 presents results (RQ1–RQ3); Section 4 discusses general insights and SC5.0 implications and future research agenda; Section 5 concludes.

METHODOLOGY

Research Design: This study adopts an SLR approach to synthesise current knowledge on PM integration with DT development and simulation methodologies. The research approach is articulated in three phases: systematic search, structured selection, and thematic analysis to address sectoral applications (RQ1), PM technique utilization (RQ2), and simulation method integration (RQ3). Figure 1 illustrates the screening.

Search Strategy and Scope: The search is carried out in the Scopus database, which was selected as the sole source because it offers the most comprehensive coverage among abstract-indexing databases for engineering, computer science, and management literature (Ren et al., 2019). The search query combined core concepts to address the intersection of PM methodologies with automated digital model generation: TITLE-ABS-KEY (("simulation" OR "system dynamic*" OR "digital twin" OR "digital model" OR "agent based model*") AND "process mining" AND ("automatic generat*" OR "concept* model*" OR "automatic* discover*" OR "process discover*")).

The focus is on papers addressing automated or semi-automated model generation through PM for simulation or DT purposes. The search was restricted to publications of the last five years, considering the DT concept's evolution and industrial adoption acceleration in recent years, in parallel with the growing maturity of PM

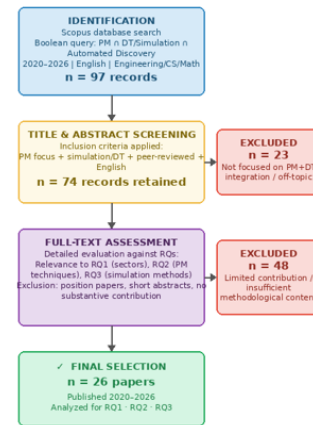


Figure 1 Systematic paper's selection process

techniques and practices, focusing on technical subject areas (e.g., Mathematics, Decision Sciences, Engineering, and Computer Science).

Selection Process: Document selection proceeded through multi-stage screening: inclusion criteria required (1) primary focus on PM techniques applied to simulation or DT development (2) peer-reviewed publication in journals or conference proceedings ensuring quality standards, and (3) English language for consistent analysis. Exclusion criteria eliminated: (1) PM papers without simulation or DT focus, (2) simulation or DT papers without PM integration, (3) position papers, editorials, or short abstracts lacking substantive methodological or empirical contributions, and (4) papers where detailed content analysis was not feasible. The initial Scopus returned 97 documents. Abstract screening against the inclusion criteria eliminated 23 contributions, leaving 74 papers for full-text assessment. Detailed evaluation of the remaining contributions' full-texts, considering the relevance to the research questions, led to the selection of 26 papers. To ensure methodological transparency, the selection process followed a structured screening protocol consistent with PRISMA guidelines and checklists (Lima et al., 2025). The screening was conducted independently by two authors: disagreements were resolved through discussion and consensus; papers were assessed for methodological clarity, reproducibility of results, and relevance to RQs (Elo & Kyngäs, 2008).

RESULTS

Descriptive Analysis: The systematic search returned 26 documents published between 2020 and 2026, revealing sustained research interest in PM-enabled DT development. The temporal distribution shows a peak in 2022 with 6 selected papers (23%), followed by steady production through 2024-2026 (10 papers combined, 38%), confirming growing interest beyond initial methodological explorations.

Sector Applications (RQ1): The analysis reveals a concentration in industrial sectors requiring complex process coordination and real-time visibility, with significantly different adoption levels across five main

sectors. *Business Process and Cross-Sector Frameworks* (57%, n=13) dominate the coverage of selected papers, providing domain-agnostic methodologies but applicable across sectors. This predominance provides a fundamental technical infrastructure that enables adoption across various sectors and thus potential expansion of application areas, it also indicates that most current research remains at a conceptual level without sector-specific empirical validation. Contribution classified in this group include simulation discovery work (Camargo et al., 2020; Chapela-Campa & Dumas, 2022; Camargo et al., 2022), new paradigm exploration including SD discovery (Pourbafrani & van Der Aalst, 2022) and ABM integration (Sulis & Taveter, 2022; Sulis, 2023; Bemthuis & Lazarova-Molnar, 2025; Baidya & Baidya, 2025) and technical advances in prediction, evaluation, and specialized modelling (Brockhoff et al., 2021; Yoshiro et al., 2024; Kalenkova et al., 2025; Bouhidel & Belala, 2023; Nedopetalski & De Freitas, 2021). The most mature application domain with the highest impact in terms of citations is *manufacturing and industrial production* (23%, n=6), which serves as the main testing ground where PM-DT methodologies are validated and refined. Key applications include automated discovery of production systems, which reduces modelling time from weeks to hours (Lugaresi & Matta, 2021b), event-centric digital models for Industry 4.0 contexts (Castiglione, 2024), equipment-centric reliability assessment integrating sensor data for predictive maintenance (Friederich et al., 2023), state-to-event abstraction solving missing event log problems (Mayr et al., 2022), and inter-organizational collaboration DTs extending across manufacturing SC tiers (Yang et al., 2022), and comprehensive multi-dimensional DTs automatically extracted via Multi-Flow Process Mining for multi-objective optimization of time, energy, and waste in manufacturing systems (Khodadadi & Lazarova-Molnar, 2026). The *construction and infrastructure* sector (9%, n=2) is an emerging sector that demonstrates a high level of innovation in adapting PM-DT to challenging contexts, beyond manufacturing. (Zhang & Lin, 2025) integrate computer vision with PM, using cameras mounted on tower cranes to generate event logs that enable real-time DES simulation for construction planning. (Wang et al., 2024) integrate workflow models discovered by PM with BIM geometric models, introducing the concept of process twins and bridging the gap between traditionally fragmented processes and representations of physical space. *Logistics and SC* areas (4%, n=1) appear underrepresented despite the urgent resilience needs. Shams-Shemirani et al. (2024) demonstrate that PM-based DES models for cross-docking facilities outperform manually constructed models in capturing operational variability, leading to superior decisions regarding allocation. This single application, while successful, highlights an important lack of adaptive decision support tools for the SC despite the disruptive pressures typical of this sector. *Industrial Cyber-Physical Systems* (4%, n=1) complete the proposed sectoral

distribution: Vitale et al. (2025) demonstrate PM-DT value for safety-critical industrial cyber-physical systems that require explainable and trustworthy models using discovered process models for both offline fault simulation and online anomaly detection with superior performance versus black-box approaches. Bemthuis & Lazarova-Molnar (2025) systematically review the PM-ABM integration opportunities for distributed autonomous systems, a concept extendable to SCs.

Process Mining Techniques (RQ2): The use of techniques reveals a clear predominance of Discovery as a fundamental capability, while Conformance Checking and Enhancement show moderate but significant adoption with distinct levels of maturity. *Process Discovery* appears in 74% of articles as a universal entry point for building PM-DT integrated models. It automatically extracts process models from event logs, enabling rapid and unbiased generation of models based on operational reality. The main applications (Camargo et al., 2020; Lugaresi & Matta, 2021b) establish methodologies for extracting control flows, resource pools, and time distributions from ERP/MES logs. Specialized contexts include Mayr et al. (2022)'s state-to-event abstraction for manufacturing environments without native event logs, Pourbafrani & van Der Aalst (2022)'s SD discovery that aggregates events to identify stock flow structures and feedback loops, and Castiglione (2024) and Yang et al. (2022)'s multi-perspective discovery that emphasizes organizational, resource, and collaboration perspectives in addition to pure control flow. These advantages are widely exploited, but some challenges remain, including the potential complexity of models, dependencies on log quality, and manual selection of the level of abstraction. *Enhancement* shows substantial adoption for refining the model beyond the initial discovery. Applications range from improving simulation accuracy through modelling extraneous delays (Chapela-Campa & Dumas, 2022) to enrichment that integrates equipment health status and organizational structures (Castiglione, 2024; Yang et al., 2022; Friederich et al., 2023), improving real-time runtime for monitoring and prediction (Vitale et al., 2025; Brockhoff et al., 2021), and collaborative human-machine improvement that enables the integration of expert knowledge (Pourbafrani et al., 2021). Although 52% adoption indicates significant industry focus on improvement, few articles demonstrate continuous improvement cycles that enable truly adaptive "living" DTs, suggesting that implementations remain more static than the paradigm's potential allows. *Conformance Checking* is the least used fundamental PM technique, despite its crucial role in validation and adaptive monitoring. Applications have two main purposes: model quality assessment through DT-specific conformance metrics that evaluate suitability, accuracy, generalization, simplicity, and operational relevance (Yoshiro et al., 2024) and monitoring runtime deviations, which enables real-time anomaly detection with explainable results superior to black-box statistical approaches (Vitale et al., 2025). Additional uses include simulation validation

(Pourbafrani et al., 2021), multi-agent compliance (Baidya & Baidya, 2025), and twin construction verification (Wang et al., 2024). The modest adoption rate (22%) represents a clear underutilization, highlighting the potential for extension in this field.

Simulation Methods (RQ3): Analysis of simulation methods reveals methodological pluralism, with DES being the most common, alongside significant adoption of Petri nets, ABM, and SD, which serve distinct purposes. *DES* remains the most widespread, but it is far from monopolistic. Articles using *DES* cover construction (Zhang & Lin, 2025; Wang et al., 2024) manufacturing (Lugaresi & Matta, 2021b; Mayr et al., 2022; Friederich et al., 2023), business processes (Camargo et al., 2020; Pourbafrani et al., 2021), and evaluation contexts (Yoshiro et al., 2024). López-Pintado et al. (2024) advance this line of work by incorporating differentiated resource modelling, discovering individual performance profiles and availability calendars from logs, and coupling simulation with optimisation to explore cost-time trade-offs. *Petri nets* mainly serve as formal intermediate representations that enable verification rather than simulation by the end user. Castiglione (2024), Friederich et al. (2023) Nedopetalski & De Freitas (2021) use *Petri nets* for the representation of production systems, reliability modelling, and hybrid resource scenarios. *Petri nets* enable formal mathematical analyses (deadlock detection, reachability verification) before implementation, particularly valuable in safety-critical contexts. Khodadadi & Lazarova-Molnar (2026) extend this paradigm by proposing a Multi-Flow Process Mining approach that extracts Multidimensional Stochastic Petri Nets capturing time, energy, and waste dimensions simultaneously, enabling multi-objective optimization in smart manufacturing systems. *ABM* represents an emerging interest, as evidenced in Bemthuis & Lazarova-Molnar (2025), who examine opportunities for PM-ABM integration, while Sulis & Taveter (2022) and Sulis (2023) demonstrate agent-based business process simulation with environmental considerations. Agent-based conceptual thinking also appears in Baidya & Baidya (2025) and Bouhidel & Belala (2023). Tour et al. (2021) introduce Agent System Mining as a framework that combines process mining with agent-based modelling to infer Multi-Agent System models directly from event data. *ABM*'s 13% adoption represents an initial exploration with significant growth potential, particularly for SC applications modelling for autonomous supplier-buyer interactions. *SD* (9%, n=2) receives minimal adoption despite its strategic value for policy-level modelling. Primary focus is on discovering PM-based system dynamics for strategic analysis (Pourbafrani & van Der Aalst, 2022) and in industrial cyber-physical systems contexts (Vitale et al., 2025).

Summary of research gaps: The review exposes five interrelated gaps that collectively constrain the practical impact of PM-DT research. First, SC and logistics applications are critically underrepresented, despite the domain's urgent need for adaptive decision-support tools and its clear compatibility with PM-DT methodologies.

Second, DT lifecycles remain predominantly static. Although PM's Enhancement capability theoretically supports continuous model adaptation, few papers demonstrate closed-loop discover-conform-enhance cycles. Most implementations are "build-once" systems, with model updating treated as a future research direction. Third, Conformance Checking is structurally underutilized, despite being the capability most directly relevant to real-time anomaly detection and proactive deviation management, functions of high value in resilient SC design. Fourth, strategic simulation via System Dynamics remains marginal, limiting the ability of PM-DT systems to support the feedback-loop analysis required by SC5.0 resilience and sustainability planning. Fifth, multi-paradigm simulation integration (combining *DES*, *SD*, and *ABM* within a unified DT architecture) is discussed conceptually but not yet implemented in any reviewed paper, leaving a critical methodological gap between theoretical proposals and operational systems. SC underrepresentation is partly a consequence of the static DT lifecycle gap (adaptive tools are harder to develop), which in turn reflects the underutilization of Conformance Checking. Addressing them requires coordinated progress across all three RQ dimensions.

DISCUSSION

The results from RQ1–RQ3 show that PM–DT performs well in manufacturing but remains misaligned with SC5.0. The following sections examine how each of the three pillars exposes specific gaps and directions for PM-DT development, as represented in Figure 2.

PM technique I / SC5.0 →	Resilience Pillar I	Sustainability Pillar II	Human- centricity Pillar III
Discovery RQ2: 74% DES · SD · ABM	SC disruption modelling via DES · SD	Environmental metrics mapping via DES — gap	Human workflow discovery via ABM — gap
Enhancement RQ2: 52% DES · SD · ABM	Post-disruption model adaptation via DES	Circ. economy & env. enrichment via SD — gap	Expert knowledge integration via ABM
Conformance Checking RQ2: 22%	Real-time disruption alerts unexplored — gap	Sustainability compliance unexplored — gap	Policy & safety monitoring unexplored — gap

Figure 2 PM-DT integration framework for SC5.0).

Pillar I) Resilience: SC5.0 resilience requires systems capable of anticipating, absorbing, and recovering from disruptions, overcoming the concept of reaction after events (Villar et al., 2023). PM-DT integration embraces this proactive approach, but current practice only partially exploits its potential. Discovery provides the empirical basis that reactive models lack. The cross-docking application by Shams-Shemirani et al. (2024) demonstrates that the models discovered by PM captured variability that deterministic manual models did not, enabling superior resource allocation decisions. Extended to multilevel SC networks, the discovery could replace idealized assumptions with empirically grounded representations of how SCs behave under normal, and disruptions. Conformance checking and, more specifically, real-time conformity checking of

operational events against identified process models could serve as a continuous interruption detection system. The application by Vitale et al. (2025) demonstrates that compliance-based anomaly detection provided more timely, accurate, and explainable detection than statistical alternatives. For SCs, early detection of critical deviations could transform reactive crisis management into proactive mitigation, thereby serving as a catalyst for SC resilience. Enhancement can be seen as a continuous learning approach: in this regard, it supports the adaptive resilience required by SC5.0. Continuous DT updates, covering supplier reliability, delivery distributions, and alternative routing, support adaptive resilience by incorporating post-crises learning.

Pillar II) Sustainability: SC5.0 considers sustainability as a fundamental design principle alongside efficiency and resilience (Brückner et al., 2025), moving beyond the concept of a constraint to be managed. The selected literature on PM-DT shows that explicit analysis of environmental metrics is only detectable in Sulis (2023). PM could radically impact sustainability parameters collection SCs: rather than relying on estimates or averages of carbon emissions, PM could extract actual data from operational event logs on modes of transport used, distances, energy consumption patterns, and wastes, providing empirically based environmental accounting at the process instance level. Current combined PM-DT research provides almost no foundation for such SC5.0 multi-objective analysis, representing an open research frontier.

Pillar III) Human-Centricity: SC5.0's human-centric pillar reframes supply chain management around worker well-being, stakeholder transparency, and human-machine collaboration (Tóth et al., 2023). This dimension is absent from current PM-DT research as a direct objective. However, PM-DT offers specific capabilities relevant to human-centric SC design. For instance, Process Discovery could reveal where human decision-making is concentrated in SC workflows, showing bottlenecks or high-cognitive-load nodes where worker support tools would be most valuable. Similarly, Conformance Checking could monitor both process performance and compliance with human-centric policies (e.g., working time regulations, ergonomic and safety protocols). Enhancement could incorporate worker feedback and operational experience as enrichment data, creating DTs that learn from human insight rather than purely from automated log data. ABM adoption offers the most natural fit for human-centric SC simulation: it represents SC actors as autonomous agents with individual decision-making capabilities, local knowledge, and objectives. Enabling domain experts to enrich automatically-discovered models with knowledge not captured in logs is already explored at a tool-development level (Pourbafrani et al., 2021), but could also be extended in terms of SC implementation since it mirrors the 5.0 vision of technology augmenting and supporting human capability (Villar et al., 2023).

Research Agenda for SC5.0-Ready PM-DT Systems: The SC5.0 framing suggests research extensions for the

three pillars, according to RQs' directions. Regarding *Resilience*, the following areas can be highlighted: (i) Multi-tier SC discovery from heterogeneous organizational data sources, addressing privacy and integration challenges across SC boundaries. (ii) Real-time conformance architectures for disruption detection, developing SC-specific deviation metrics and threshold calibration. (iii) Continuous enhancement mechanisms that learn from disruption responses and incorporate post-crisis operational adaptations. (iv) SD discovery for strategic resilience simulation, extending existing methodologies with iterative loops along the SC. From a *Sustainability* perspective: (i) PM-based extraction of actual environmental metrics from SC event logs, replacing estimated or averaged carbon footprint with actual process data. (ii) Multi-objective simulation to evaluate trade-offs between sustainability, resilience, and costs through integrated DES-SD approaches. (iii) Conformance monitoring for sustainability compliance. (iv) Enhancement incorporating circular economy, reverse logistics, and responsible sourcing practices as model dimensions. For *Human-Centricity*: (i) Discovery of human decision patterns in SC workflows, identifying high-value intervention points for worker support tools. (ii) ABM architectures representing SC actors as autonomous decision-making agents, with human behavioural rules mined from event logs, aimed at empowering the operator's expertise. (iii) Collaborative enhancement frameworks combining automated PM discovery with knowledge enrichment from human experts. (iv) DT transparency and explainability requirements for SC operators, ensuring model outputs support rather than replace human judgment. From a cross-sectoral perspective, research should focus on multi-paradigm integration combining DES (operational), SD (strategic), and ABM (autonomous actors) within unified SC-DT architectures. Moreover industry-academia partnerships to translate theoretical methodologies into real-world implementations, such as standardized SC-DT evaluation frameworks, are fundamental.

Limitations: This SLR acknowledges some constraints: the reliance on Scopus as the sole database, the temporal restriction from 2020 onwards, and the specific focus on PM-DT integration. The SC5.0 framing introduces an interpretive lens absent in the analysed papers themselves, due to the recent development of the 5.0 paradigm and its more complex application at the SC level compared to the single-firm level.

CONCLUSIONS

This SLR analysed papers addressing PM integration with DT development and simulation, revealing a field with strong methodological foundations, selective sectoral maturity, and significant research opportunities. This review's primary contributions are twofold. First, it provides the first comprehensive synthesis of PM-DT integration research, systematically mapping sectoral applications, PM technique and simulation method adoption. Second, it offers novel insights into how PM-

DT integration could address SC resilience and sustainability challenges through Discovery and Conformance checking, and Enhancement-driven continuous learning from operational experience. The proposed research agenda targets the identified gaps and carries practical implications for SC managers, organisations, and researchers. As complexity, uncertainty, and disruptions increase within SCs and networks, the need for adaptive decision-support tools intensifies and. PM-enabled DTs can be fundamental.

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REFERENCES

- van der Aalst, W. (2016) Data Science in Action. In: W. van der Aalst ed. *Process Mining: Data Science in Action*. Springer: Berlin, Heidelberg, pp.3–23. https://doi.org/10.1007/978-3-662-49851-4_1, accessed 17 February 2026.
- Baidya, A. & Baidya, S.S. (2025) A Multi-agent Framework for Autonomous Process Mining and Optimization. *Journal of Advances in Information Technology*, **16** (10): 1487–1500.
- Beerepoot, I., Di Ciccio, C., Reijers, H.A., Rinderle-Ma, S., Bandara, W., Burattin, A., Calvanese, D., Chen, T., Cohen, I., Depaire, B., Di Federico, G., Dumas, M., van Dun, C., Fehrer, T., Fischer, D.A., Gal, A., Indulska, M., Isahagian, V., Klinkmüller, C., Kratsch, W., Leopold, H., Van Looy, A., Lopez, H., Lukumbuzya, S., Mendling, J., Meyers, L., Moder, L., Montali, M., Muthusamy, V., Reichert, M., Rizk, Y., Rosemann, M., Röglinger, M., Sadiq, S., Seiger, R., Slaats, T., Simkus, M., Someh, I.A., Weber, B., Weber, I., Weske, M. & Zerbato, F. (2023) The biggest business process management problems to solve before we die. *Computers in Industry*, **146**: 103837.
- Bemthuis, R.H. & Lazarova-Molnar, S. (2025) Towards integrating process mining with agent-based modeling and simulation: State of the art and outlook. *Expert Systems with Applications*, **281**: 127571.
- Bouhidel, S.I. & Belala, N. (2023) Unleashing the Power of Process Mining for Discovering and Analyzing Ad Hoc Networks. In: *Int. Conf. Netw. Adv. Syst., ICNAS*. Institute of Electrical and Electronics Engineers Inc.
- Bozorgi, Z.D., Teinemaa, I., Dumas, M., La Rosa, M. & Polyvyanyy, A. (2020) Process Mining Meets Causal Machine Learning: Discovering Causal Rules from Event Logs. In: *2020 2nd International Conference on Process Mining (ICPM)*. pp.129–136. <https://ieeexplore.ieee.org/document/9230023>, accessed 17 February 2026.
- Brockhoff, T., Heithoff, M., Koren, I., Michael, J., Pfeiffer, J., Rumpe, B., Uysal, M.S., Van Der Aalst, W.M.P. & Wortmann, A. (2021) Process Prediction with Digital Twins. In: *Companion Proc. - Int. Conf. Model-Driven Eng. Lang. Syst., MODELS-C*. Institute of Electrical and Electronics Engineers Inc., pp.182–187.
- Brückner, A., Wölke, M., Hein-Pensel, F., Schero, E., Winkler, H. & Jabs, I. (2025) Assessing industry 5.0 readiness—Prototype of a holistic digital index to evaluate sustainability, resilience and human-centered factors. *International Journal of Information Management Data Insights*, **5** (1): 100329.
- Camargo, M., Dumas, M. & González-Rojas, O. (2020) Automated discovery of business process simulation models from event logs. *Decision Support Systems*, **134**: 113284.
- Camargo, M., Dumas, M. & González-Rojas, O. (2022) Learning Accurate Business Process Simulation Models from Event Logs via Automated Process Discovery and Deep Learning. In: X. Franch, G. Poels, F. Gailly, & M. Snoeck eds *Advanced Information Systems Engineering*. Springer International Publishing: Cham, pp.55–71.
- Castiglione, C. (2024) Automated generation of digital models for manufacturing systems: The event-centric process

- mining approach. *Computers and Industrial Engineering*, **197**.
- Chapela-Campa, D. & Dumas, M. (2022) Modeling Extraneous Activity Delays in Business Process Simulation. In: *2022 4th International Conference on Process Mining (ICPM)*. pp.72–79. <https://ieeexplore.ieee.org/document/9980544/>, accessed 17 February 2026.
- Difrancesco, R.M. & Klumpp, M. (2025) Supply Chain Management 5.0 – How to Conceptualize Network Cascading and Implementation of Human-centric Operations. *IFAC-PapersOnLine*, **59** (10): 2016–2021.
- Elo, S. & Kyngäs, H. (2008) The qualitative content analysis process. *Journal of Advanced Nursing*, **62** (1): 107–115.
- Friederich, J., Cai, W., Gan, B.P. & Lazarova-Molnar, S. (2023) Equipment-centric Data-driven Reliability Assessment of Complex Manufacturing Systems. In: *ACM Int. Conf. Proc. Ser. Association for Computing Machinery*, pp.62–72.
- Ivanov, D. & Dolgui, A. (2021) A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control*, **32** (9): 775–788.
- Kalenkova, A., Mitchell, L. & Roughan, M. (2025) Performance Analysis: Discovering Semi-Markov Models From Event Logs. *IEEE Access*, **13**: 38035–38053.
- Khodadadi, A. & Lazarova-Molnar, S. (2026) Automated extraction of comprehensive digital twin models for smart manufacturing systems. *Journal of Manufacturing Systems*, **85**: 287–306.
- Kritzing, W., Karner, M., Traar, G., Henjes, J. & Sihn, W. (2018) Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, **51** (11): 1016–1022.
- Lay, J.L., Neveu, J., Dalmas, B. & Augusto, V. (2022) Automated Generation of Patient Population for Discrete-Event Simulation Using Process Mining. In: *2022 Annual Modeling and Simulation Conference (ANNSIM)*. pp.42–53. <https://ieeexplore.ieee.org/document/9859406/>, accessed 17 February 2026.
- Lima, M.S. de, Farina, A.G., Nelson Kadel, J. & Sellitto, M.A. (2025) Alternatives and Benchmarking for Implementations of Waste-to-Energy from Municipal Solid Waste: A Systematic Review. *Resources*, **14** (12). <https://www.mdpi.com/2079-9276/14/12/185>, accessed 1 April 2026.
- López-Pintado, O., Dumas, M. & Berx, J. (2024) Discovery, simulation, and optimization of business processes with differentiated resources. *Information Systems*, **120**: 102289.
- Lugaresi, G. & Matta, A. (2021a) Automated Digital Twins Generation for Manufacturing Systems: a Case Study. *IFAC-PapersOnLine*, **54** (1): 749–754.
- Lugaresi, G. & Matta, A. (2021b) Automated manufacturing system discovery and digital twin generation. *Journal of Manufacturing Systems*, **59**: 51–66.
- Mayr, M., Luftensteiner, S. & Chasparis, G.C. (2022) Abstracting Process Mining Event Logs from Process-State Data to Monitor Control-Flow of Industrial Manufacturing Processes. In: *Procedia Comput. Sci.* Elsevier B.V., pp.1442–1450.
- Nedopetalski, F. & De Freitas, J.C.J. (2021) Process Mining and Simulation for a p-Time Petri Net Model with Hybrid Resources. In: *IEEE Syst. Inf. Eng. Des. Symp., SIEDS*. Institute of Electrical and Electronics Engineers Inc.
- Overbeck, L., Brützel, O., Teufel, M., Stricker, N., Kuhnle, A. & Lanza, G. (2021) Continuous adaption through real data analysis turn simulation models into digital twins. *Procedia CIRP*, **104**: 98–103.
- Pourbafrani, M. & van Der Aalst, W.M.P. (2022) Discovering System Dynamics Simulation Models Using Process Mining. *IEEE Access*, **10**: 78527–78547.
- Pourbafrani, M., Jiao, S. & van der Aalst, W.M.P. (2021) SIMPT: Process Improvement Using Interactive Simulation of Time-Aware Process Trees. In: *Lect. Notes Bus. Inf. Process.* Springer Science and Business Media Deutschland GmbH, pp.588–594.
- Ren, S., Zhang, Y., Liu, Y., Sakao, T. & Et., A. (2019) A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions. *Journal of Cleaner Production*. <https://sci-hub.box/10.1016/j.jclepro.2018.11.025>, accessed 2 April 2026.
- Shams-Shemirani, S., Tavakkoli-Moghaddam, R., Amjadian, A. & Motamedi-Vafa, B. (2024) Simulation and process mining in a cross-docking system: a case study. *International Journal of Production Research*, **62** (13): 4902–4925.
- Sulis, E. (2023) Agent-Based Simulations and Process Mining: A Green BPM Case Study. In: F. Squazzoni ed. *Advances in Social Simulation*. Springer Nature Switzerland: Cham, pp.337–344.
- Sulis, E. & Taveter, K. (2022) *Agent-Based Business Process Simulation: A Primer with Applications and Examples*. Springer International Publishing.
- Tao, F., Zhang, H., Liu, A. & Nee, A.Y.C. (2019) Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*, **15** (4): 2405–2415.
- Tóth, A., Nagy, L., Kennedy, R., Bohuš, B., Abonyi, J. & Ruppert, T. (2023) The human-centric Industry 5.0 collaboration architecture. *MethodsX*, **11**: 102260.
- Tour, A., Polyvyanyy, A. & Kalenkova, A. (2021) Agent System Mining: Vision, Benefits, and Challenges. *IEEE Access*, **9**: 99480–99494.
- Villar, A., Paladini, S. & Buckley, O. (2023) Towards Supply Chain 5.0: Redesigning Supply Chains as Resilient, Sustainable, and Human-Centric Systems in a Post-pandemic World. *Operations Research Forum*, **4** (3): 60.
- Vitale, F., Guarino, S., Flammini, F., Faramondi, L., Mazzocca, N. & Setola, R. (2025) Process Mining for Digital Twin Development of Industrial Cyber-Physical Systems. *IEEE Transactions on Industrial Informatics*, **21** (1): 866–875.
- Wang, Y., Liao, S., Gong, Z., Deng, F. & Yin, S. (2024) Enhancing Construction Management Digital Twins Through Process Mining of Progress Logs. *Sustainability (Switzerland)*, **16** (22).
- Yang, M., Moon, J., Jeong, J., Sin, S. & Kim, J. (2022) A Novel Embedding Model Based on a Transition System for Building Industry-Collaborative Digital Twin. *Applied Sciences (Switzerland)*, **12** (2).
- Yoshiro, J., Lopes, P.V., Neto Verri, F.A. & Skoogh, A. (2024) How to evaluate process discovery for digital twins in industry 4.0? Process discovery, hypothesis testing, and conformance analysis. In: *Proc. - Eur. Conf. Model. Simul., ECMS*. European Council for Modelling and Simulation, pp.178–184.
- Zhang, H. & Lin, C. (2025) Computer vision and process mining-based simulation model generation for construction planning and control. *Automation in Construction*, **179**.