

Advancements in Smart Manufacturing and Industry 4.0

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1. Introduction

The ongoing digitalization of industry continues to reshape production systems through cyber–physical integration [1], pervasive IoT connectivity [2], advanced analytics [3], and AI-driven decision support [4]. While Industry 4.0 [5] lays the technological foundation—data acquisition, interoperability, and automation—its evolution toward Industry 5.0 [6] centers human wellbeing, resilience, and sustainability as co-equal objectives with productivity. This Special Issue gathers studies that (i) optimize shop-floor processes via data-driven and learning-based methods [7], (ii) propose decentralized and verifiable architectures for logistics and shared services [8], (iii) examine organizational adoption and qualification frameworks necessary for regulated domains [9], and (iv) advance human-centric models that sustain energy, skills, and trust [10]. Together, the contributions demonstrate how smart manufacturing moves beyond isolated pilots to scalable, socio-technical systems that deliver measurable business value while reducing environmental impact and strengthening human roles [11]. The following overview presents each contribution in sequence, highlighting its aims, methods, main findings, and implications for research and practice.

2. An Overview of Published Articles

Contribution 1—“Optimization of Intelligent Maintenance System in Smart Factory Using State Space Search Algorithm”.

This paper develops and evaluates an Intelligent Maintenance System (IMS) that integrates IIoT sensing, SCADA data streams, and a Computerized Maintenance Management System (CMMS) to reduce unplanned downtime. The authors introduce a State Space Search (SSS) optimization layer that synthesizes equipment condition, risk profiles (aligned with FMEA), and cost models to produce optimal maintenance schedules. The architecture formalizes the automation pyramid and connects historical maintenance records with real-time parameters, enabling dynamic trade-offs among cost, risk, and remaining useful life. Empirical analyses show that coupling SSS with IMS yields maintenance cycles that minimize cost while extending asset lifetimes, thereby improving availability. Methodologically, the work demonstrates how search-based optimization can be embedded into day-to-day asset management without disrupting existing workflows. For practitioners, the concept provides a route to systematically prioritize interventions where predictive signals are strong, and defer when risks remain acceptable, converting reactive maintenance into a risk-aware, data-driven program. For researchers, the study opens avenues to benchmark search heuristics under heterogeneous failure distributions, fuse multi-sensor prognostics into the objective functions, and quantify organizational factors (staffing, spares logistics) that influence the realized value of intelligent maintenance at scale.



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Contribution 2—“Artificial Intelligence Model Used for Optimizing Abrasive Water Jet Machining Parameters to Minimize Delamination in CFRP”.

Focusing on abrasive water jet (AWJ) piercing of CFRP, the authors train a feed-forward ANN to predict delamination risk as a function of process settings. AWJ piercing involves high-energy impact; mis-tuning can cause interlaminar damage, scrap, and costly rework—especially in aerospace and automotive CFRP parts. The ANN, trained with backpropagation on experimentally labeled data, learns non-linear relationships among jet pressure, stand-off distance, traverse speed, abrasive mass flow, and other parameters. Validation shows the model can recommend parameter sets that eliminate delamination, effectively turning a sensitive operation into a controllable one. The contribution underscores three points: first, learning-based surrogates can complement physics-based intuition in brittle-laminate processing; second, optimizing the entry phase (piercing) is pivotal for downstream quality; and third, the approach reduces trial-and-error time and consumables, improving sustainability. Future work could hybridize the ANN with uncertainty quantification to provide confidence bounds on parameter windows, extend to complex layups and nozzle wear states, and couple recommendations to in-process sensing for closed-loop control, thus generalizing the method from static recipe selection to adaptive machining.

Contribution 3—“HumanEnergy Hotspot: Conceptual Design of an Agile Toolkit for Human Energy Reinforcement in Industry 5.0”.

This design-science study proposes HumanEnergy Hotspot, an agile toolkit that operationalizes human-centricity by reinforcing employee energy, wellbeing, and creative capacity within digitally intensive factories. Combining Design Science Research with Human-Centered Design, the authors deliver modular artifacts—workshop methods, reflective prompts, sensing-informed routines, and managerial checklists—that organizations can tailor across roles and contexts. The toolkit complements technical transformation roadmaps by addressing human energy as a first-class system variable, critical for sustained adoption of automation and advanced analytics. The manuscript positions the toolkit within the EU’s Industry 5.0 agenda, detailing how interventions can be integrated into continuous improvement cycles, leadership practices, and skill development. While conceptual, the work sets a foundation for empirical validation, such as measuring impacts on engagement, safety behavior, creativity, and error rates. It also encourages alignment with digital ergonomics and ethical AI guidelines. For practitioners, HumanEnergy Hotspot offers a low-barrier entry to codify human-centric practices; for researchers, it suggests experimental designs to quantify causal links between energy reinforcement and operational KPIs under varying automation levels.

Contribution 4—“Artificial Intelligence Software Adoption in Manufacturing Companies”.

Leveraging data from the European Manufacturing Survey 2022 across Slovenia, Slovakia, and Croatia, this paper analyzes determinants of AI software adoption in six production areas. Contrary to common assumptions, firm size, supply-chain role, and technology intensity are not statistically significant predictors of AI use. Instead, Industry 4.0 readiness—the maturity of digital infrastructure and CPS integration—emerges as the dominant correlate. The implication is clear: AI uptake depends less on structural descriptors and more on digital preparedness (connectivity, data quality, interoperability). For management, the findings reframe adoption strategies toward building robust data pipelines, standardization, and cross-functional capabilities before scaling AI applications. For policy and ecosystem actors, they highlight the leverage of programs that raise baseline digital maturity (standards, testbeds, vouchers) rather than size- or sector-based targeting. The study invites longitudinal follow-ups to track causality, investigate organizational learning curves, and examine complementarities between AI and workforce upskilling, particularly where human-in-the-loop decision processes are critical.

Contribution 5—“Cybernetic Model Design for the Qualification of Pharmaceutical Facilities”.

Addressing regulated manufacturing, the authors synthesize eight years of project experience to propose a cybernetic model for qualification of pharmaceutical facilities aligned with Pharma 4.0. The model closes feedback loops across risk management, experimental verification, numerical simulation, and optimization while maintaining compliance with regulatory expectations. It structures qualification as an adaptive control problem: inputs (process design, equipment specs, utilities) are tested against quality attributes and risk scenarios; outputs (deviations, learnings) feed forward into design and commissioning. Case applications demonstrate improved traceability, responsiveness, and energy savings, with the model proving flexible for reconstructions and upgrades. The contribution is notable for bridging project management and systems engineering—transforming qualification from a document-heavy checkpoint into a learning system. Future research can formalize metrics for time-to-qualification, cost-of-nonconformance, and digital thread completeness; investigate interoperability with GxP-compliant data lakes; and extend the cybernetic approach to continuous process verification in biologics and personalized medicine.

Contribution 6—“Monitoring Equipment Malfunctions in Composite Material Machining: Acoustic Emission-Based Approach for Abrasive Waterjet Cutting”.

This work deploys acoustic emission (AE) sensing to supervise AWJ cutting of CFRP, aiming to detect emerging equipment malfunctions without intrusive instrumentation. By mapping AE features to machine and process states, the method identifies anomalies indicative of nozzle wear, unstable jet behavior, or fixture issues, all of which degrade cut quality. The approach offers several advantages: it is non-destructive, installable with minimal process disruption, and suited to complex CFRP geometries common in aerospace and automotive sectors. The authors demonstrate discriminative AE signatures for malfunction categories and discuss thresholds for actionable alerts, supporting a shift from periodic inspection to condition-based intervention. For practitioners, AE monitoring promises fewer defects and rework, better surface integrity, and extended component life. For researchers, the study motivates fusing AE with high-frequency pressure/flow telemetry and vision post-inspection, and training multi-modal classifiers that robustly generalize across thicknesses, layups, and abrasive types.

Contribution 7—“The Evaluation of Industry 5.0 Concepts: Social Network Analysis Approach”.

Using data from 146 manufacturing companies (European Manufacturing Survey, Serbia), this paper applies social network analysis and related methods to map Industry 5.0 enablers across human-centricity, sustainability, and resilience. The results identify task-specific training as a central human-centric indicator; material efficiency measures as pivotal for sustainability; and standardized, detailed work instructions as critical for resilience. The analysis clarifies how these factors interrelate within organizational practice, offering a grounded lens on the Industry 5.0 discourse that often remains conceptual. For policymakers and firm leaders, the findings encourage investment in competence development tied to production tasks, rigorous work standardization that supports adaptive responses, and material usage programs that deliver both environmental and cost benefits. The study also points to network-based diagnostics as a tool to prioritize interventions and track transitions from Industry 4.0 readiness to Industry 5.0 outcomes.

Contribution 8—“Smart Manufacturing Application in Precision Manufacturing”.

Presenting a multi-year industrial case, this paper operationalizes a six-gear smart factory roadmap—connectivity, integration, and analytics—using off-the-shelf technologies in precision manufacturing. Quantified benefits include +47% machine utilization, −53% downtime, GBP 420k cost savings with <1-year payback, and a 43% GHG reduction

(notably –50% Scope 2 emissions) via energy management. The work is significant for closing the gap between strategy and execution: it details the technical architecture, change management, and a replicable sequencing of capabilities that de-risks deployment for SMEs. The study demonstrates that meaningful environmental gains can coincide with productivity improvements when energy telemetry and operations analytics are embedded in daily routines. Limitations (integration complexity, data governance) are discussed candidly, and the roadmap offers a scalable template for firms seeking competitive advantage and decarbonization without bespoke platforms.

Contribution 9—“Decentralized Public Transport Management System Based on Blockchain Technology”.

This paper proposes a blockchain-enabled framework for intelligent transportation systems featuring tokenized vehicles (macro-tokens subdivided into micro-tokens), a mathematical model for vehicle health, and the GDEPZ method to optimize satellite data transmission. The approach aims to deliver transparent fleet management, predictive maintenance, and tamper-evident records in hard-to-reach regions. While centered on public transport, the architecture generalizes to shared manufacturing and distributed asset services, where verifiable state, provenance, and condition monitoring are essential. Organizational benefits include reduced manipulation risk, shorter decision chains, and extended asset life. For industry, the contribution highlights how verifiable ledgers can bind heterogeneous stakeholders (operators, service providers, insurers) into trustworthy workflows. Future lines include integrating on-chain/off-chain analytics, privacy-preserving telemetry, and smart contracts that automate service-level enforcement for industrial fleets and mobile production units.

Contribution 10—“Modeling and Analysis of Intrabody Communication for Biometric Identity in Wireless Body Area Networks”.

Investigating galvanic intrabody communication (IBC) channels, the authors analyze signal loss across human subjects and use K-Nearest Neighbors to model biometric identification, achieving 99.9% identification accuracy on curated datasets. The study elucidates how anthropometric and tissue characteristics influence channel gain variability and proposes a WBAN architecture embedding identification as a first-class function. Although the application domain is biomedical, the implications extend to proximal industrial IoT and human–machine interfacing, where secure, body-bound signaling can mitigate spoofing risks and support operator authentication in safety-critical zones. The work invites future research on robustness under motion, perspiration, and electromagnetic noise typical of factories, and explores combining IBC with continuous authentication schemes and privacy safeguards suitable for industrial settings.

Contribution 11—“Exploring Decentralized Warehouse Management Using Large Language Models: A Proof of Concept”.

This proof of concept explores LLM-mediated decentralized coordination for warehouse operations in the context of shared manufacturing. Agentic LLMs orchestrate tasks—picking, slotting, exception handling—across distributed resources, interfacing with IoT and legacy systems. The study surfaces benefits (flexible task allocation, natural-language configurability) and risks (hallucination, controllability, safety). The authors suggest guardrails: constrained action spaces, verification layers, and audit trails to maintain reliability. The contribution is timely, pointing toward agentic operations where language interfaces reduce integration friction and enable rapid adaptation. For practice, it frames a pathway to pilot narrow, well-bounded use cases (e.g., inbound checks, discrepancy triage) before scaling. For research, it motivates benchmarks for safety-critical planning, deterministic tool use, and hybrid architectures combining symbolic planners with LLM reasoning to ensure traceability and compliance.

Contribution 12—“Sustainable Optimization of the Injection Molding Process Using Particle Swarm Optimization (PSO)”.

Targeting injection molding, the authors combine a backpropagation neural network (BPNN) surrogate with particle swarm optimization (PSO) to jointly meet strict quality targets (weight, thickness) while minimizing energy and material waste. Compared to trial-and-error, the hybrid reduced optimization time by ~40% and improved predictive accuracy (reported RMSEs for thickness and weight), enabling SMEs to reach CAE-like precision without costly software. Experimental validation indicates –28% energy and –35% waste, with estimated –22% production cost through combined savings. The framework exemplifies a practical, replicable route to data-driven sustainability: use a lightweight learner to map parameter–quality relationships; apply metaheuristics to find Pareto-efficient setpoints; and validate on-line to institutionalize gains. Future work could extend to multi-material molding, integrate uncertainty-aware PSO, and co-optimize cycle time and scrap rates under varying ambient conditions and machine health states.

Contribution 13—“Systematic Analysis of Risks in Industry 5.0 Architecture”.

This review consolidates risk taxonomies and mitigation strategies for Industry 5.0 architectures, spanning CPS vulnerabilities, data governance, human-factor risks, and organizational processes. By classifying assets, platform-independent risks, and countermeasures, it provides a reference model for designing secure, human-centric systems. The synthesis emphasizes security by design, continuous monitoring, and alignment with ethical and regulatory frameworks. For practitioners, it offers a checklist to embed controls throughout the lifecycle—requirements, integration, operation—rather than treating security as an add-on. For researchers, it identifies gaps in measuring human-centric risk impacts (fatigue, cognitive overload), interdependencies among AI assurance, safety, and privacy, and the need for standardized evaluation of resilience in mixed human–AI teams operating under uncertainty.

3. Conclusions and Future Directions

Across these contributions, four themes recur: (1) AI-enabled operational excellence, where learning-based surrogates and search/metaheuristics upgrade maintenance, machining, and molding; (2) decentralized and verifiable operations, leveraging blockchain and agentic LLMs for transparent coordination beyond the single factory; (3) human-centric transformation, with tools and empirical evidence placing skills, energy, and wellbeing at the heart of performance; and (4) assurance and compliance, via cybernetic qualification models and comprehensive risk frameworks. Looking ahead, we foresee three priority directions: (i) closed-loop autonomy that binds sensing, learning, and robust control with certified safety; (ii) socio-technical integration that couples human-energy reinforcement and competence building with digital twins and interoperable data spaces; and (iii) green performance by design, where energy, waste, and circularity metrics are co-optimized with throughput and quality. We thank the authors and reviewers for their rigorous efforts and the *Applied Sciences* Editorial Office for their support. Together, these works chart a pragmatic path from fragmented pilots to scalable, trustworthy, and sustainable smart manufacturing.

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