



# Manufacturing Digitalization as a Substitute for Scale: How Data Compensates for Capital Scarcity

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## Abstract

*This article examines how small and medium-sized manufacturing firms can pursue growth through data-driven management when capital is scarce and scale-based competition is unattainable. The topic gains urgency as expansion via additional floor space, equipment, and headcount becomes increasingly costly, while firms face rising expectations for controllability, reliable lead times, and transparent unit economics. The study's novelty lies in formalizing a digital-first manufacturing model in which managerial decisions rely on short data cycles rather than capacity-expansion investments. The paper describes an architecture of digital control, featuring ERP as the planning and accounting backbone, CRM as a channel for market and customer feedback, and KPI systems as instruments of operational steering, and explains how performance metrics and data governance rules can substitute for scale. It further analyzes practical patterns of rapid operational adjustment under resource constraints. The research uses analytical synthesis of recent studies and conceptual modeling to substantiate the mechanism by which data create scale-like effects without comparable capital outlays. The conclusion outlines managerial implications and conditions for applying the model in capital-intensive sectors.*

**Keywords:** Manufacturing Digitalization, Data-Driven Management, Scale Substitution, Capital Constraints, ERP, CRM, KPI, MES, Operational Efficiency, Short Data Cycles.

## INTRODUCTION

Small and medium manufacturing enterprises (SMEs) routinely face a structural constraint: competitive pressure rewards speed, reliability, and customization, while access to capital for expanding equipment, floor space, and headcount remains limited. Under such conditions, scale-based competition becomes a fragile strategy, as marginal growth through assets increases fixed costs more rapidly than managerial control. The article develops a digital-first manufacturing model in which data flows, integrated systems, and KPI-driven control loops replicate several effects commonly attributed to scale—process predictability, coordination efficiency, and learning speed—without matching capital intensity. The objective is to substantiate how data-centric management compensates for capital scarcity and to formalize an architecture that connects production control (ERP/MES), market feedback (CRM-side signals), and operational steering (KPI loops). The paper's tasks are:

- i) to specify a digital-first control architecture for manufacturing SMEs;
- ii) to explain the substitution mechanisms by which data and systems reduce the need for scale and capital;
- iii) to derive an analytically grounded roadmap for fast managerial adjustments through short data cycles using evidence from recent empirical and review studies.

## MATERIALS AND METHODS

The evidence base draws on recent peer-reviewed and institutional research on digital transformation and data-driven manufacturing. F. Balaha [1] synthesizes ERP-Industry 4.0 integration research for decision support and identifies recurring adoption frictions (interoperability, cybersecurity, skills). A. Bhaskar [2] validates a structured ERP-Lean integration model in an automotive tooling SME and links digitized traceability and standardized work to operational improvement. A. Bianchini [3] proposes a systematic approach to embedding a KPI framework through MES deployment in a manufacturing SME, emphasizing the move from "big data" accumulation to "smart data" for performance assessment. L. Compagnucci [4] reviews digital B2B platforms enabling manufacturing transformation and discusses governance and value-creation mechanisms across supply networks. The ESCB expert group report [5] consolidates firm-level and sector-level evidence on productivity channels of digitalisation and stresses complementarities (skills, intangible investments, governance). L. L. Moreira

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[6] applies the Alkire–Foster method to benchmark SME digital transformation profiles and highlights the skills, despite infrastructure challenges. Njah [7] develops a digital maturity model tailored to manufacturing SMEs, framing modular progress under financial constraints. E. Peretz-Andersson [8] explains AI implementation in manufacturing SMEs through a resource orchestration lens (structuring, bundling, leveraging capabilities). F. Schwark [9] studies how digitalization alters production functions and links digital correlates to structural shifts in intensity. D. Wang [10] provides empirical evidence that manufacturing digital transformation improves performance through efficiency gains and cost reduction pathways.

For writing the article, the following methods were applied: structured literature analysis, comparative synthesis across empirical and review studies, conceptual modeling of a digital-first control loop, and analytic generalization to derive transferable managerial implications for manufacturing SMEs.

### RESULTS

The reviewed evidence supports a consistent analytical proposition: when capital expansion is constrained, managerial controllability becomes the primary growth bottleneck, and data-centric systems primarily act on controllability rather than on physical capacity. This reframes “scale” from a stock of assets into a stream of decisions executed with low latency and high traceability. Studies connecting digital transformation to performance commonly attribute gains to improvements in operational efficiency and cost reduction mechanisms, rather than to mere technology adoption signals, implying that performance uplift is mediated by how well data are embedded into routines, control, and coordination [10].

A digital-first manufacturing model begins with the unification of operational truth: one set of master data for items, routings, work centers, and orders, and one transaction along with a unified backbone for commitments and actuals. ERP occupies the position of cross-functional integration and auditability, especially when Industry 4.0 technologies introduce heterogeneous data sources. Systematic review evidence highlights that ERP integration with Industry 4.0 technologies (notably IoT, big data analytics, and cloud computing) is repeatedly linked to real-time visibility and process optimization potential, while practical barriers cluster around complexity, interoperability, cybersecurity, and workforce readiness [1]. In a capital-scarce setting, such integration acts as a substitute for “managerial headcount scale”: instead of adding layers of supervision, the enterprise encodes control through standardized digital workflows and data validations.

At the shop-floor level, MES-enabled instrumentation converts equipment and operator events into time-stamped operational data that directly feeds KPI computation.

Evidence from MES implementation in a manufacturing environment shows an explicit, revealing, and logical focus on building a comprehensive, developing, and performance assessment system, as well as framing a work grounded in product-based data [3]. The substitution mechanism here is structural: instead of investing in redundant buffers (extra machines, extra inventory, extra overtime), the firm invests in measurement granularity and uses KPI signals to reduce variance. Over time, variance reduction lowers the capital required for the same service level because safety buffers shrink when process capability and predictability rise.

The strongest operational articulation of “data replacing scale” emerges when ERP discipline is coupled with Lean routines and traceability. A validated ERP–Lean integration in an automotive mould manufacturing SME is reported as a structured, phased approach where digitized standard operating procedures, traceability, and changeover improvements are integrated into a single, replicable framework [2]. Conceptually, this pairing shifts improvement from artisan problem-solving to institutional learning: each deviation becomes a data record, each corrective action becomes a template, and repeated micro-losses become visible. The economic meaning for a small plant is direct: learning speed substitutes for asset scale, because faster learning compresses the time needed to reach stable throughput and stable quality at existing capacity.

To make this logic operational, the model requires a short-cycle control loop that links (a) measurement, (b) diagnosis, and (c) intervention selection. The literature on decision support and integrated systems repeatedly frames integrated data as the prerequisite for predictive insights and for near-real-time operational intelligence in manufacturing environments [1]. Within the proposed model, short cycles function as a “data flywheel”: frequent KPI refresh reduces decision latency; reduced latency lowers the amplitude and duration of process drift; more negligible drift reduces the need for costly corrective buffers; buffers freed from firefighting are redirected to targeted improvements. In the absence of experimental data, the analytical leverage lies in aligning mechanisms reported across independent studies: the Wang et al. empirical pathway “digital transformation → higher efficiency / lower costs → higher performance” is consistent with the MES-to-KPI logic (measurement → control) and with ERP–Lean traceability (standardization → repeatable improvement) [3,10].

Market and customer signals enter the production system through the commercial data layer—a CRM-like feedback loop, which includes k streams, service tickets, demand volatility indicators, and quotation-to-order analytics. While the selected sources emphasize manufacturing systems more than CRM per se, digital B2B platform research provides an adjacent mechanism: when digital platforms reduce transaction frictions and improve information flow across networks, small manufacturers can access demand

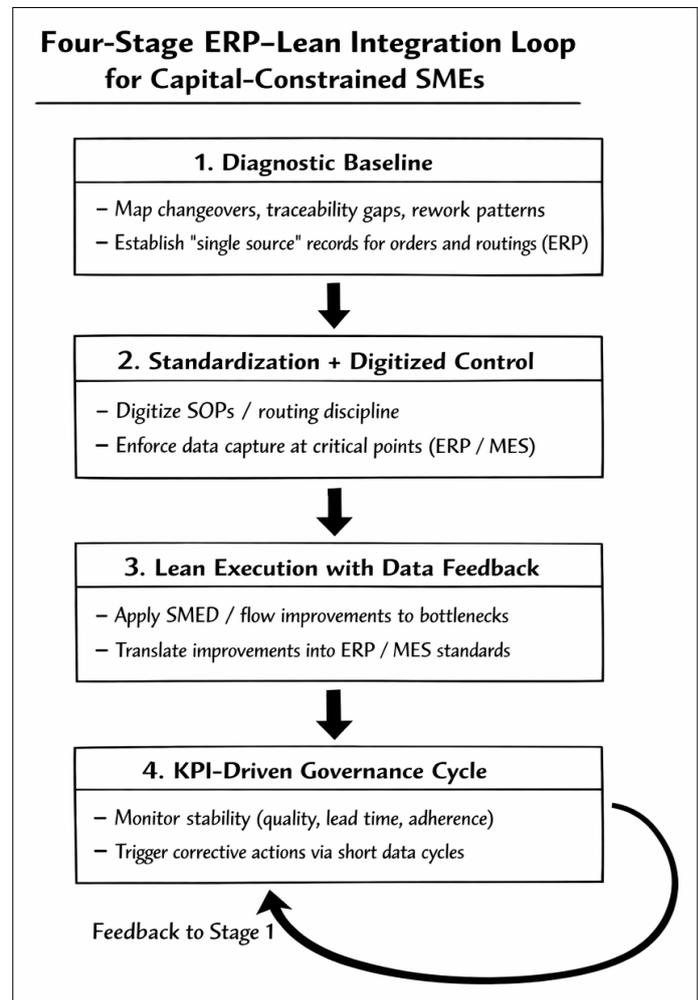
and partner resources more efficiently, partially substituting for internal scale [4]. In a digital-first model, this translates into a planning benefit: demand signals become structured inputs for scheduling priorities and capacity planning, thereby reducing the penalty associated with forecast error.

Resource constraints and uneven capabilities create a practical boundary condition: adoption needs to be modular and maturity-aware. A manufacturing SME digital maturity model explicitly frames financial constraints and limited skills as distinguishing conditions, responding by designing a multidimensional indicator structure intended to guide a staged transition toward Industry 4.0 [7]. Complementary evidence suggests that many SMEs possess a baseline infrastructure yet still exhibit capability gaps, particularly in digital skills supply and demand, which directly limits the speed at which data loops can be institutionalized [6]. Consequently, “data replacing capital” works only after a minimum capability threshold: data collection without governance, ownership, and interpretive skill produces noise and administrative burden rather than controllability [11].

A further amplification of the model is AI-enabled decision support, but its feasibility in SMEs depends on orchestration rather than relying solely on algorithms. Evidence on AI implementation in manufacturing SMEs suggests that progress involves structuring, bundling, and leveraging resources and capabilities; learning and governance are identified as prerequisites for sustainable AI use in operations [8]. In the proposed model, AI is positioned downstream of integration: ERP/MES data consistency serves as the “substrate,” while governance constrains how recommendations are translated into actions (e.g., scheduling rules, quality gates, maintenance triggers). This ordering reduces capital pressure by preventing “AI-first” procurement cycles that often require heavy investment before measurable operational benefit.

At the macro-structural level, the substitution narrative gains theoretical support from production-function evidence. Digitalisation is associated with changes in substitution patterns, and sectors with higher digital capital exhibit higher elasticity of substitution in key input relationships; the study further. This differentiates among types of digital capital, highlighting information technology and software/databases as consequential components [9]. While this work is not SME-specific, it supports a general economic interpretation: digital capital changes how it affects the effectiveness with which inputs are transformed into outputs, enabling organizational designs where information substitutes for certain physical specifics and coordination costs. Complementary institutional synthesis notes that productivity gains from digitalisation are heterogeneous and depend on complementary investments (skills, intangible assets, governance), implying that digital-first manufacturing is a managerial design problem rather than a procurement checklist [5].

Figure 1 is integrated below as a simplified representation of the ERP–Lean staged integration logic adapted from the validated SME framework reported by Bhaskar and Devaraju [2].



**Figure 1.** Four-stage ERP–Lean integration loop for capital-constrained manufacturing SMEs (adapted from [2])

Each stage reduces reliance on capital buffers by converting variability into managed, measurable, and correctable signals. The loop closes when KPI governance consistently turns deviations into standardized interventions; at that point, learning velocity becomes a functional substitute for scale, because the organization continuously re-optimizes without expanding its asset base.

**DISCUSSION**

The evidence synthesized in the Results section supports a managerial conclusion that I consider operationally decisive for manufacturing SMEs: digitalisation contributes most when it converts uncertainty into a structured control regime, and it contributes least when it remains an “IT layer” disconnected from shop-floor routines and decision rights. The reviewed ERP–Industry 4.0 literature repeatedly highlights interoperability, cybersecurity, and skills as adoption constraints [1], and the ECB emphasizes complementarities—institutions, such as governance

structures, workforce skills, and intangible investments—as key investments, essential for productivity gains [5]. When capital is scarce, these complementarities become the real investment frontier: money saved on additional machines is effectively reallocated into data discipline, training, and

process ownership, which is more challenging to imitate and more complex to expand.

Table 1 translates the “data replacing scale” proposition into concrete substitution mechanisms across the ERP/MES/KPI loop [1–3,5,10]

**Table 1.** Data-driven substitutes for scale and capital in digital-first manufacturing SMEs

Scale/capital problem in SMEs	Data-driven substitute inside the model	Operational manifestation
Limited supervisory capacity	Encoded control through integrated workflows	ERP-based routings, approvals, and traceability gates reduce manual coordination
Need for large safety buffers	Variance reduction via KPI control loops	Short-cycle KPI refresh triggers targeted interventions, reducing buffer inventory/overtime reliance
Costly capacity expansion	Throughput stabilization at existing assets	Changeover reduction and standardized work increase adequate capacity without new equipment
Hidden cost drivers	Cost transparency through structured transaction data	Cost-to-serve and rework drivers become visible and correctable
Low learning speed	Institutional learning via digitized standards	SOP updates follow measured deviations; knowledge persists beyond individuals
Fragmented productivity impact	Complementary investments (skills/intangibles)	Training + governance determine whether digital tools convert to productivity.

Attempting AI optimization before ERP/MES data are reliable often produces brittle models and high maintenance costs. The resource orchestration view of AI adoption in manufacturing SMEs frames success as a capability-building process rather than as a one-off deployment [8]. This aligns with the maturity-model logic that advocates modular progress under constraints [7]. In my assessment, the practical implication is a strict sequencing rule: integration and governance are prioritized first, followed by optimization later. Not because AI lacks value, but because the capital-scarce firm cannot afford long feedback loops that fail to translate into daily operational control.

Table 2 operationalizes this sequencing as a staged roadmap tied to maturity constraints and to the complementary conditions emphasized in the evidence.

**Table 2.** Sequencing roadmap for capital-constrained digital-first manufacturing [1–3,5–8]

Stage (minimal viable target)	What is implemented	Primary capability constraint	Expected managerial gain
1. Integration baseline	ERP master data discipline; unified order truth	Data ownership and basic literacy	Reduced planning ambiguity; fewer coordination errors
2. Measurement granularity	MES/event capture for critical operations; KPI definitions	Shop-floor adoption, data quality routines	Stable visibility of losses; faster diagnosis
3. Standardized control	Digitized SOPs; traceability gates; Lean routines connected to ERP	Process ownership and governance	Repeatable improvements; less rework and drift
4. Modular expansion	Targeted digital modules (maintenance, quality analytics)	Skills depth and change management	Higher uptime and adherence; lower variability
5. Optimization layer	AI/advanced analytics for scheduling/quality prediction	Capability bundling and governance maturity	Decision support that scales expertise

The substitution claim—data compensating for capital—requires careful delineation of its boundary conditions. Production-function evidence suggests structural changes associated with digital capital intensity [9], but firm-level outcomes remain heterogeneous and dependent on complementarity [5]. Hence, the model is not a universal shortcut; it is a disciplined management system that reallocates scarce resources from physical scaling to controllability scaling. In capital-intensive industries, I expect the model to be especially relevant where variability and coordination costs dominate unit economics (e.g., high-mix low-volume environments), because reducing variance yields “virtual capacity” without expanding assets. At the same time, cybersecurity and interoperability constraints identified in ERP–Industry 4.0 integration research can impose nontrivial overhead [1]; in my judgment, ignoring these constraints is the fastest way to convert a digital-first initiative into a cost center rather than a scale substitute.

### CONCLUSION

The developed digital-first manufacturing model substantiates the paper's objective by formalizing how integrated systems and short-cycle KPI governance reproduce several effects commonly attributed to scale under capital scarcity. First, the architecture specification clarifies a functional division: ERP anchors cross-functional truth and traceability, MES-level capture feeds operational measurement, and KPI loops translate measurement into repeatable interventions supported by standardized digital rules, consistent with evidence on ERP-Industry 4.0 decision support and MES-enabled KPI frameworks. Second, the substitution mechanisms are analytically grounded in empirical pathways that link digital transformation to performance through efficiency and cost reduction, as well as in validated SME cases where ERP-Lean coupling institutionalizes learning through digitized traceability and SOP discipline. Third, the roadmap logic aligns adoption with manufacturing SME constraints and with complementarity requirements emphasized in productivity syntheses and maturity/AI capability research, supporting modular progress rather than capital-heavy "big bang" transformations.

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