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Production Flow Improvement and Value Stream Mapping in Digitally Enabled Lean Manufacturing: An Integrated Framework Linking Digital Enablers to Sustainability Outcomes

Emad Rabiei Hosseinabad

Northern Illinois University/Department of Industrial and Systems Engineering, DeKalb, USA

Abstract: Existing reviews of lean manufacturing, digital technology and sustainability usually cover one or two of these areas at a time, and none of the reviews identified in this study examine lean tools, digital enablers, functional domains and sustainability outcomes side by side. This paper addresses that gap by developing a three-layer framework that links four digital enablers (artificial intelligence, the Internet of Things, blockchain and digital twins) to operational efficiency, environmental and social outcomes across production, logistics and warehousing, alongside lean tools such as value stream mapping, Kaizen and heijunka as its base. The method is a structured narrative review. Furthermore, the research classified sources by domain, enabler, lean tool, sustainability focus and evidence type, then combined the labels into a framework. Most of the evidence comes from literature reviews, and the only firm-level studies focus on production. Each domain utilizes a different enabler. Sustainability is rarely stated as a primary focus and is absent from the production-focused articles. Heijunka is the least studied lean tool in a digital setting. The originality of this study lies in combining all four elements into one framework that future research in production, logistics, and warehousing can evaluate. Moreover, the paper's practical contribution is to provide a clear guide for plant and supply chain or logistics managers, expressed via four propositions for future research to examine. Together, these propositions can help assess lean maturity before investing in an enabler, feed value stream maps with continuous flow data, utilize artificial intelligence scheduling for heijunka, and report operational efficiency, environmental and social measures.

Keywords: lean manufacturing, value stream mapping, Kaizen, heijunka, digital twin, Industry 4.0, sustainability, supply chain management

INTRODUCTION

Lean manufacturing aims to remove waste from the way work moves through a plant. It grew out of the Toyota Production System (Ohno, 1988) and was generalized by Womack and Jones (2003), who start from what the customer values and trace every step that delivers it. Empirical work treats lean as a bundle of practices rather than a single technique, and tests those bundles against plant context and operational performance (Shah & Ward, 2003). It is critical to indicate that three tools are central to most shop-floor programs: value stream mapping (VSM), Kaizen and heijunka.

VSM draws the material and information flow of a product family so that delay and waste become visible (Rother & Shook, 2018). Hines and Rich (1997) proposed seven mapping tools, each matched to a type of waste. Kaizen is continuous, incremental improvement. In a study of Japanese manufacturers, Brunet and New (2003) found that it develops differently

in each organization and that all the firms used it to meet targets. Heijunka levels production volume and mix over time, and Miltenburg (1989) supplied the scheduling theory for keeping part usage constant on mixed-model assembly lines.

Digital technologies now sit on top of these tools. Reviews have mapped and classified machine learning applications in manufacturing (Cioffi et al., 2020; Wuest et al., 2016), and artificial intelligence (AI) techniques are reviewed for supply chains as well (Toorajipour et al., 2021). Research on the Internet of Things (IoT) in supply chain and logistics management remains mostly conceptual, with few analytical or empirical studies (Ben-Daya et al., 2019). Blockchain has been reviewed for the barriers to its adoption (Saberi et al., 2019) and for its role in sustainability (Zhang et al., 2025). Digital twins lack a shared definition in production logistics (Kaiblinger & Woschank, 2022). Maheshwari et al. (2024) later conceptualized a digital twin for warehouse management. A large body of work already links lean with Industry 4.0, the digital connection of production systems. Sanders et al. (2016) argued that Industry 4.0 can help overcome barriers to lean implementation. Tortorella and Fettermann (2018) found in Brazilian firms that lean practices are positively linked to Industry 4.0 technologies, and that adopting both together gives larger performance gains. Rossini et al. (2019) reported that European manufacturers with widely implemented lean practices may find Industry 4.0 easier to adopt, while weak process design and a missing improvement routine can hold readiness back. Systematic reviews now cover the combined field (Buer et al., 2018; Saad et al., 2024) and continuous improvement strategies such as Kaizen alongside Industry 4.0 (Vinodh et al., 2021). On VSM in particular, a survey of 170 participants found its main weakness to be limited flexibility, and 92% of the experts wanted it developed further with digital tools (Lugert et al., 2018).

Sustainability has been added to this work in two ways. Dües et al. (2013) reviewed how lean practices can support green initiatives in the supply chain, and how green practices can strengthen lean in return. On the digital side, Kamble et al. (2018) reviewed 85 papers and proposed a sustainable Industry 4.0 framework that links technologies, process integration and sustainable outcomes, and Bai et al. (2020) built a sustainability framework from the United Nations Sustainable Development Goals to assess Industry 4.0 technologies. This paper uses the triple bottom line of economic, environmental and social results (Elkington, 1997) as its outcome frame. The closest reviews each cover one aspect of the framework. Serevan and Kuşakcı (2026) focus on machine learning in lean tools, Ali and Phan (2022) on Industry 4.0 in sustainable warehousing, and Winkelhaus and Grosse (2020) on logistics. As their abstracts describe them, none of the three sets enablers, functional domains, sustainability outcomes and lean tools side by side. This paper therefore addresses one central question: how do artificial intelligence, the Internet of Things, blockchain and digital twins connect to operational efficiency, environmental and social outcomes in manufacturing production, logistics and warehousing, and where do VSM, Kaizen and heijunka support those connections?

MATERIALS AND METHODS

This study adopts a structured narrative review with a framework synthesis. The sources were identified, checked, classified and compared in the four steps outlined below so that other researchers can follow the same approach in comparable settings.

1. Search: keyword searches were run on a general web search service, not on Scopus or Web of Science. Each query combined a lean term (lean manufacturing, value stream mapping, Kaizen, heijunka), a digital term (artificial intelligence, machine learning, Internet of Things, blockchain, digital twin, Industry 4.0) and a domain term (production, logistics, warehousing), and some added a sustainability term. Examples are "digital twin warehouse logistics systematic literature review" and "artificial intelligence machine learning lean manufacturing production leveling heijunka review". Title searches followed for works already known in the field, such as the lean foundations.
2. Selection: A source was maintained if it was a peer-reviewed journal article, or a book cited for a lean definition; if it addressed lean practice, a named digital enabler or sustainability in manufacturing, logistics or warehousing; and if it was written in English. Review articles were preferred for trend claims because they summarize many primary studies. Foundational works of any date were kept for lean concepts.
3. Verification: For every candidate, the author names, year, title, venue, volume and pages were compared with the publisher or repository record, and the DOI was recorded where that record showed one, and over 25 sources were confirmed and kept.
4. Classification and synthesis: The author classified the 27 journal articles published from 2013 onward to focus on relevant studies from their abstracts and bibliographic records on five fields: domain (production, logistics, warehousing or cross-domain); digital enabler (AI, IoT, blockchain, digital twin, Industry 4.0 in general, or none); lean tool as the primary subject (VSM, Kaizen, heijunka, other lean practice or none); sustainability as a stated focus (yes or no, judged against the economic, environmental and social outcomes of the triple bottom line); and evidence type (literature review, firm-level data or other). Definitions came from the four earlier journal articles (1989 to 2003) and four books, which were not classified. The labels were cross-tabulated by domain and enabler, Figure 1 framework was developed by organizing the lean tools, the enablers and the outcomes in layers.

The reported counts below are descriptive. Articles were classified based on their abstracts and bibliographic records without full text review. The search did not include a dedicated bibliographic database, so coverage is not exhaustive; however, the sample spans 2013 to 2026, covers three functional domains and all four enablers, which makes it a good indication of where the review evidence is concentrated and where gaps remain.

RESULTS

Sample and Overall Pattern

The 27 classified articles split across domains as follows: 11 on production, 7 on logistics and supply chains, 4 on warehousing and 5 that span domains. Twenty-one are literature reviews. Three report firm-level data: a survey on VSM (Lugert et al., 2018) and two on lean and Industry 4.0 (Rossini et al., 2019; Tortorella & Fettermann, 2018). All three sit in production. By enabler, Industry 4.0 in general is the most common subject (10 articles), followed by AI (5), blockchain (3), IoT or smart warehouse technology (2), digital twins (2) and digital tools for VSM (2). Three articles name no single enabler. Only four articles take

one of the three lean tools as their main subject: VSM (2), Kaizen (1) and heijunka (1). Sustainability is a stated focus in 9 of the 27.

An Integrated Framework

Figure 1 places the findings in three layers. At the base, each lean tool has its own task. VSM shows where flow stalls, Kaizen turns what is seen into improvement, and heijunka holds volume and mix steady. The middle layer holds the four enablers. IoT captures data, AI turns data into predictions and schedules, and digital twins give a virtual counterpart of a physical flow, although definitions still vary (Kaiblinger & Woschank, 2022). The last line in each box lists the domains that enabler appears in. Blockchain records transactions that several firms need to trust, and its reported benefits include traceability, visibility and process transparency (Munir et al., 2022). At the top sit the three outcomes: efficiency, environmental results and social results.

Each link in the figure has some support in the sample, though the strength varies. VSM has two sources: pairing it with simulation, big data and IoT widens its use (Liu & Zhang, 2023), and surveyed experts mostly wanted the method developed with digital tools (Lugert et al., 2018). Kaizen has one source, a review of continuous improvement strategies alongside Industry 4.0 (Vinodh et al., 2021). For heijunka, the review literature names optimization-based problem solving and links with Industry 4.0 as two of its three topics (Boutbagha & El Abbadi, 2024). On the outcome side, efficiency gains are the best documented (Serevan & Kuşakcı, 2026), while environmental and social links come mainly from warehousing and blockchain reviews (Ali & Phan, 2022; Munir et al., 2022). The framework synthesizes reported links and has not been tested.

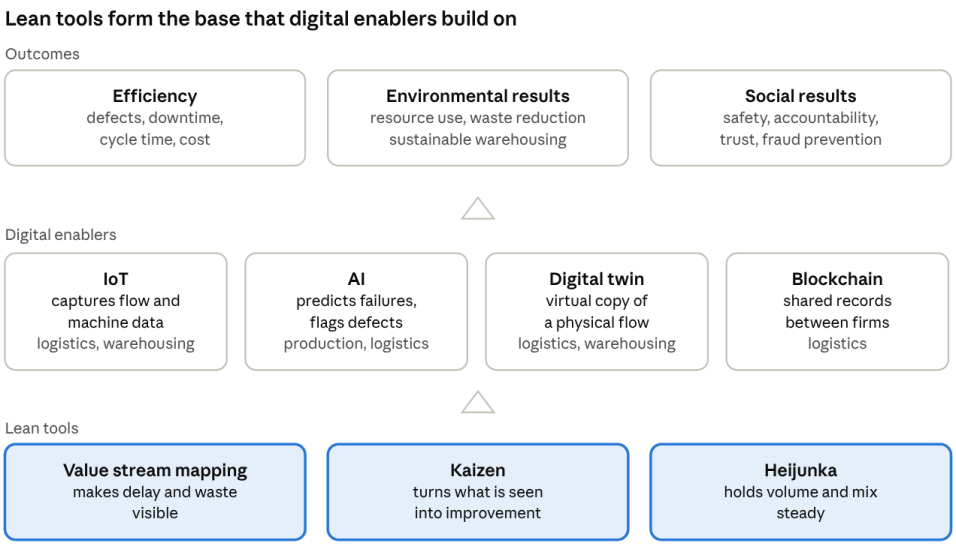

Figure 1: Framework linking lean tools, digital enablers and sustainability outcomes

Production

Four of the 11 production articles concern AI, mostly as machine learning. In a review of articles published between 2010 and May 2025, Serevan and Kuşakcı (2026) found supervised

and deep learning most common, applied mainly to predictive maintenance, quality control, defect detection and process monitoring. The lean tools most often paired with machine learning were total productive maintenance, quality control, just-in-time and VSM. The reported gains were in defect rates, downtime, cycle time, cost and safety, and the authors caution that their size varies by context. Projects benefited from data quality, sensor and IT infrastructure, management support and workforce readiness, and were held back by integration complexity, skill gaps, weak standardization and limited empirical validation. Powell (2024) adds that current AI use in lean manufacturing mostly optimizes production systems without human involvement, and that only a limited amount of research combines AI and lean in the sustainable, resilient and human-centric terms of Industry 5.0.

On VSM, the survey by Lugert et al. (2018) and the bibliometric review by Liu and Zhang (2023) agree on direction: static maps are limiting, and digital pairing extends their use. None of the abstracts in the sample describes a continuously updated map evaluated in a plant. Heijunka is the thinnest area. Boutbagha and El Abbadi (2024) reviewed 60 articles and found that it has received little academic attention. Heijunka also does not appear among the most frequently targeted lean tools in the machine learning review above, although Miltenburg (1989) had already framed leveling as a scheduling problem with algorithmic solutions.

Logistics

Seven articles cover logistics and supply chains, and blockchain is the largest group among them (3 of 7). IoT research in supply chains is mostly conceptual, with few analytical or empirical studies (Ben-Daya et al., 2019). AI techniques have been reviewed across logistics, marketing, supply chain and production (Toorajipour et al., 2021), and Winkelhaus and Grosse (2020) built a Logistics 4.0 framework from 114 articles that links external drivers, core technologies, the effects of human interaction and logistics functions. Blockchain is the only enabler in this domain whose reviews are organized around sustainability. Saberi et al. (2019) sorted adoption barriers into inter-organizational, intra-organizational, technical and external groups. Zhang et al. (2025), reviewing 69 papers published between 2008 and 2023, built a framework for sustainability-focused adoption. Munir et al. (2022) reviewed 136 articles by triple bottom line and reported economic gains from traceability, visibility and process transparency, together with environmental and social benefits such as better resource use, accountability, trust and fraud prevention. They also examined adoption barriers in industries such as aviation, shipping, agriculture and food, and textiles. Digital twins are less settled. Kaiblinger and Woschank (2022) reviewed their use in production logistics and found no shared view of how they are built and used.

Warehousing

Four articles cover warehousing. Zhen and Li (2022) organized a review of smart warehouse operations around information interconnection, equipment automation, process integration and environmental sustainability. Ali and Phan (2022) linked Industry 4.0 technologies positively to the economic, social and environmental pillars of sustainable warehousing. They also listed gaps: few large-scale empirical studies, uneven attention to the three pillars, partial adoption of the technologies, and an imbalance across warehouse activities

and technologies. Boysen et al. (2019) surveyed warehouse systems and operating adaptations for e-commerce fulfillment. Maheshwari et al. (2024) conceptualized a digital twin for warehouse management and discussed interoperability, scalability and maintenance. None of the four takes a lean tool as its main subject.

Comparison Across Domains

Table 1: Comparison of the 27 classified articles by domain

Domain	Articles	Lean tool as main subject	Enablers in the sources	Sustainability as stated focus	Main gap
Production	11	3 (VSM 2, heijunka 1)	AI (4), Industry 4.0 in general (4), digital tools for VSM (2), no single enabler (1)	0 of 11	Sustainability and human-centric outcomes; heijunka; validation beyond surveys
Logistics	7	0	Blockchain (3), AI (1), IoT (1), digital twin (1), Industry 4.0 in general (1)	3 of 7	No lean link; IoT evidence mostly conceptual; no shared digital twin definition
Warehousing	4	0	Digital twin (1), smart warehouse technology (1), Industry 4.0 in general (1), no single enabler (1)	2 of 4	No lean link; few large-scale empirical studies; uneven coverage of the three pillars
Cross-domain	5	1 (Kaizen)	Industry 4.0 in general (4), no single enabler (1)	4 of 5	Reviews and frameworks rather than plant-level tests

The table shows three contrasts. First, lean tools sit almost entirely in production, and so does every article with firm-level data, while sustainability as a stated focus sits entirely outside it. Second, each domain leans on a different enabler: AI and Industry 4.0 in general in production (8 of 11), blockchain in logistics (3 of 7), and digital twins and smart warehouse technology in warehousing (2 of 4). Third, the evidence is mostly review-based everywhere, and the sources say so themselves (Ali & Phan, 2022; Ben-Daya et al., 2019; Serevan & Kuşakcı, 2026).

FUTURE RESEARCH DIRECTIONS

Figure 1 puts lean tools at the base and digital enablers above them. Rossini et al. (2019) support that order: European manufacturers with widely implemented lean practices may find Industry 4.0 easier to adopt. Tortorella and Fettermann (2018) found the two positively linked in Brazilian firms, and Sanders et al. (2016) argued that influence also runs the other way, because Industry 4.0 can help overcome barriers to lean implementation. The two survey studies show association, so the layering should be read as a pattern, not as proof of cause. The across domains count adds a point that no individual review could make point alone. Ben-Daya et al. (2019), Ali and Phan (2022) and Serevan and Kuşakcı (2026) each found thin empirical evidence in their own areas, and the classified sample shows the same thinness across all three domains.

On sustainability, Dües et al. (2013) argued that lean practices can support green initiatives, and Bai et al. (2020) and Kamble et al. (2018) offered frameworks that tie Industry 4.0 to sustainability goals. Yet none of the 11 production articles has sustainability

as a stated focus. Blockchain shows the opposite imbalance: all three blockchain reviews focus on logistics, and from their abstracts do not address shop-floor flow.

Four propositions follow from this synthesis, none of which has been evaluated.

1. Feeding VSM with continuous flow data should keep maps current and shorten the time between finding waste and acting on it.
2. AI-based scheduling is a natural approach for digitizing heijunka, because the method has algorithmic theory (Miltenburg, 1989) but limited empirical evidence of digital implementation.
3. Lean maturity should be assessed before investing in an enabler, because weak process design can reduce readiness (Rossini et al., 2019).
4. Production studies should report an environmental and a social measure alongside operational efficiency, allowing three outcomes to be compared across domains.

CONCLUSION

This review integrates lean tools, digital enablers, functional domains and sustainability outcomes into one framework, while the reviews identified here treated them separately. For managers in production, logistics and warehousing, it demonstrates which enablers the sampled literature ties to which domain and where the evidence less examined, so that an enabler investment can be compared with the lean practices already in use. For researchers, it highlights where plant-level evidence is missing and presents four propositions for future research to assess.

This review has some constraints. The search was performed on a general web service, and the sample includes 27 articles, so the findings should be interpreted within this sample, not as the whole body of the literature. Further work can evaluate the four propositions in plant studies that report operational efficiency, environmental and social measures together, for example a continuously updated value stream map and an AI-based leveling schedule in the same plant. Lean tools and digital enablers are integrated in layers: VSM, Kaizen and heijunka form the base, and the four enablers supply data, predictions, models and shared records. The evidence is primarily review-based, firm-level data appears in only 3 of the 27 articles, all focused on production. Each domain relies on a different enabler: AI and Industry 4.0 are mainly applied in production, blockchain in logistics, and digital twins and smart warehouse technology in warehousing. Heijunka is the least studied lean tool in a digital setting, and sustainability is a stated focus in 9 of the 27 articles but in none of the 11 on production-focused articles. Therefore, this paper provides insights into the least-studied topics within the lean framework, highlighting areas that can further guide future research in this field.

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