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Integrating Value Stream Mapping with Industry 4.0 Technologies for Continuous Monitoring and Control: A Literature Review

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Abstract

Value Stream Mapping (VSM) is widely used in lean manufacturing to analyze material and information flows; however, its conventional application remains largely limited to static and periodic analysis. In manufacturing settings that are becoming more digital and dynamic, this application scope limits VSM's ability to help with continuous and data-driven decision-making. This study conducts a systematic literature review that explores the application of VSM in the context of Industry 4.0 and digital manufacturing technologies. The review synthesizes research on traditional VSM, Industry 4.0 capabilities, and emerging Digital VSM concepts to identify recurring patterns, methodological limitations, and unresolved research gaps. The synthesis shows that existing integration approaches are predominantly fragmented and tool-centric, emphasizing localized digital enhancements rather than systematic value stream monitoring and control. Based on these findings, the study derives a conceptual framework for Digital Value Stream Mapping (DVSM). The framework links lean value stream logic with digital data acquisition, analytical evaluation, and monitoring and control mechanisms within a unified conceptual structure. Rather than proposing a prescriptive system design, the framework clarifies how VSM can evolve toward continuous, data-driven value stream management. By consolidating dispersed research and structuring the role of digital technologies in value stream management, this study provides a conceptual basis for future empirical investigation and for the development of consistent performance indicators to support digital value stream monitoring and control. The proposed framework is the base for future research work, which will clarify all concepts, tools, and methods that will be used to convert the framework into an implemented model.

Keywords
Lean Manufacturing; Value Stream Mapping; Industry 4.0; Digital Value Stream; Smart Manufacturing.

1. Introduction
Value Stream Mapping (VSM) is a core lean manufacturing tool used to analyze material and information flows to identify waste and improve process performance. Previous research has validated its effectiveness as a diagnostic instrument, particularly in stable and repetitive production environments characterized by relatively constant process conditions (Abdulmalek and Rajgopal 2007; Hines and Rich 1997). However, traditional VSM is inherently static and relies on manually collected data that represent processes at a specific point in time. As a result, this provides limited support for analyzing variability, real-time disturbances, and dynamic interactions within modern production systems. Several studies have reported that these characteristics reduce the applicability of conventional VSM in increasingly complex and interconnected manufacturing environments (Forno et al. 2014; Romero and Arce 2017).

At the same time, manufacturing environments have undergone substantial transformation with the adoption of Industry 4.0 technologies, including the Internet of Things (IoT), cyber-physical systems, and data analytics. These technologies enable continuous data collection, real-time system visibility, and faster feedback for operational decision-making. Prior studies indicate that such capabilities can enhance lean practices by improving transparency and responsiveness across production processes; however, they do not automatically translate into improved lean tool performance without structured integration (Buer, Strandhagen, and Chan 2018; Vaidya, Ambad, and Bhosle 2018).

In this context, researchers have increasingly explored the digitalization of VSM, often referred to as Digital VSM or VSM 4.0. Existing studies report potential benefits from simulation-based models, agent-based systems, and real-time data integration. Nevertheless, these contributions frequently remain limited to specific tools or localized applications, rather than addressing the role of VSM as a continuous monitoring and control mechanism within digitally enabled manufacturing systems (Huang et al. 2019; Meudt, Metternich, and Abele 2017).

Although the literature demonstrates growing interest in combining VSM with Industry 4.0 technologies, the current body of research largely treats them as parallel initiatives rather than as an integrated methodological system. Consequently, there is limited clarity on how digital technologies should be embedded across the stages of value stream analysis. Based on this review, this study synthesizes existing research to identify these limitations and derives a conceptual framework that clarifies how VSM can evolve to support digital transformation in the monitoring and control of value streams through Industry 4.0 concepts and tools.

This study contributes to the literature by systematically synthesizing existing research on the integration of Value Stream Mapping and Industry 4.0 technologies and by deriving a coherent conceptual framework for Digital Value Stream Mapping that supports continuous, data-driven value stream monitoring and control.

1.1 Objectives

- Systematically synthesize existing literature on value stream mapping and Industry 4.0 integration.
- Identify the limitations of traditional VSM in the context of smart manufacturing systems.
- Propose a conceptual framework that integrates Industry 4.0 technologies with VSM to support real-time value stream monitoring and control.
- Provide a base for theoretical and practical insights to guide future empirical research and industrial implementation of Digital VSM.

2. Research and Review methodology

2.1 Review Design

This study adopts a structured literature review to examine how Value Stream Mapping (VSM) has been addressed in the context of Industry 4.0 and digital manufacturing technologies. The review is designed to move beyond descriptive aggregation and instead focus on analytical synthesis, with the explicit objective of identifying conceptual patterns, methodological limitations, and unresolved gaps that inform the development of an integrated Digital Value Mapping framework.

Rather than treating VSM and Industry 4.0 as independent research streams, the review explicitly focuses on studies that address their interaction, either directly or indirectly, in the context of value stream analysis and with particular attention to approaches that enable monitoring and control of value streams through digital technologies, to proposed integrating framework for monitoring and controlling value stream mapping via digital technology.

2.2 Identification and Screening

The literature search was conducted using Web of Science as the primary database, complemented by Scopus to ensure broader research coverage. The search strategy combined keywords related to VSM, manufacturing systems, and digital technologies, including: “Value Stream Mapping”, “VSM”, “manufacturing”, “Industry 4.0”, “I4.0”, “digital”, and “technology”. Boolean operators were applied to capture studies addressing both value stream analysis and digital manufacturing concepts.

The initial search returned 662 records. Titles and abstracts were screened to exclude publications that addressed Industry 4.0 or lean manufacturing in isolation without relevance to value stream analysis. Following this screening process, studies that explicitly discussed VSM, its digitalization, or its application within technology-enabled manufacturing environments were retained for detailed analysis. Duplicate records were removed, and emphasis was placed on peer-reviewed studies with clear relevance to the research scope, including both highly cited and conceptually significant contributions. Additionally, the conceptual research about these methodologies has been selected to ensure that the main concepts are covered in this review.

2.3 Selection and exclusion Criteria

The following criteria guided the final selection of studies:
Inclusion criteria:

(i) studies addressing Value Stream Mapping or closely related value stream analysis methods.
(ii) studies involving Industry 4.0 technologies or digital manufacturing concepts.
(iii) studies that explicitly or implicitly examined the interaction between VSM and digital technologies.

Exclusion criteria included studies focusing solely on lean tools without reference to value streams, or on Industry 4.0 technologies without application to value stream analysis. Only peer-reviewed journal articles and well-established conference proceedings published in English were considered. Both conceptual and empirical studies were retained to capture theoretical developments as well as applied perspectives.

2.4 Analytical Classification

The selected studies were analyzed using a thematic classification approach. Each publication was examined with respect to its treatment of VSM, the role assigned to digital technologies, and the intended function of value stream analysis within the manufacturing system.

Based on this analysis, the literature was classified into three main groups:

(i) Studies addressing traditional VSM concepts and limitations.
(ii) Studies examining Industry 4.0 technologies as enablers of manufacturing and lean practices.
(iii) Studies proposing or discussing integrated approaches combining VSM with digital technologies.

This classification enabled systematic comparison across studies and supported the identification of recurring methodological assumptions, technological emphases, and reported limitations.

2.5 Synthesis and Derivation

The review emphasizes cross-study synthesis rather than isolated case interpretation. Particular attention was given to how studies conceptualize the role of VSM (diagnostic versus continuous), the degree of digital integration achieved, and the performance indicators used to evaluate outcomes.

Recurring limitations identified across the literature, such as the static nature of VSM, tool-centric digitalization approaches, and the absence of continuous monitoring mechanisms, were consolidated into a set of research gaps. These gaps provide the analytical basis for deriving the conceptual framework presented in the subsequent section and implementing the model in future research.

Accordingly, the proposed Digital Value Stream Mapping framework is not introduced as a standalone proposal but as a synthesized outcome grounded in the collective findings of the reviewed literature and the requirement for future research to enhance monitoring and control of value stream mapping via digital technology. This study adopted the research methodology and the literature synthesis process outlined in Figure 1. The figure summarizes the main stages of literature identification, screening, classification, and synthesis, which inform the identification of research gaps and the derivation of the conceptual framework.

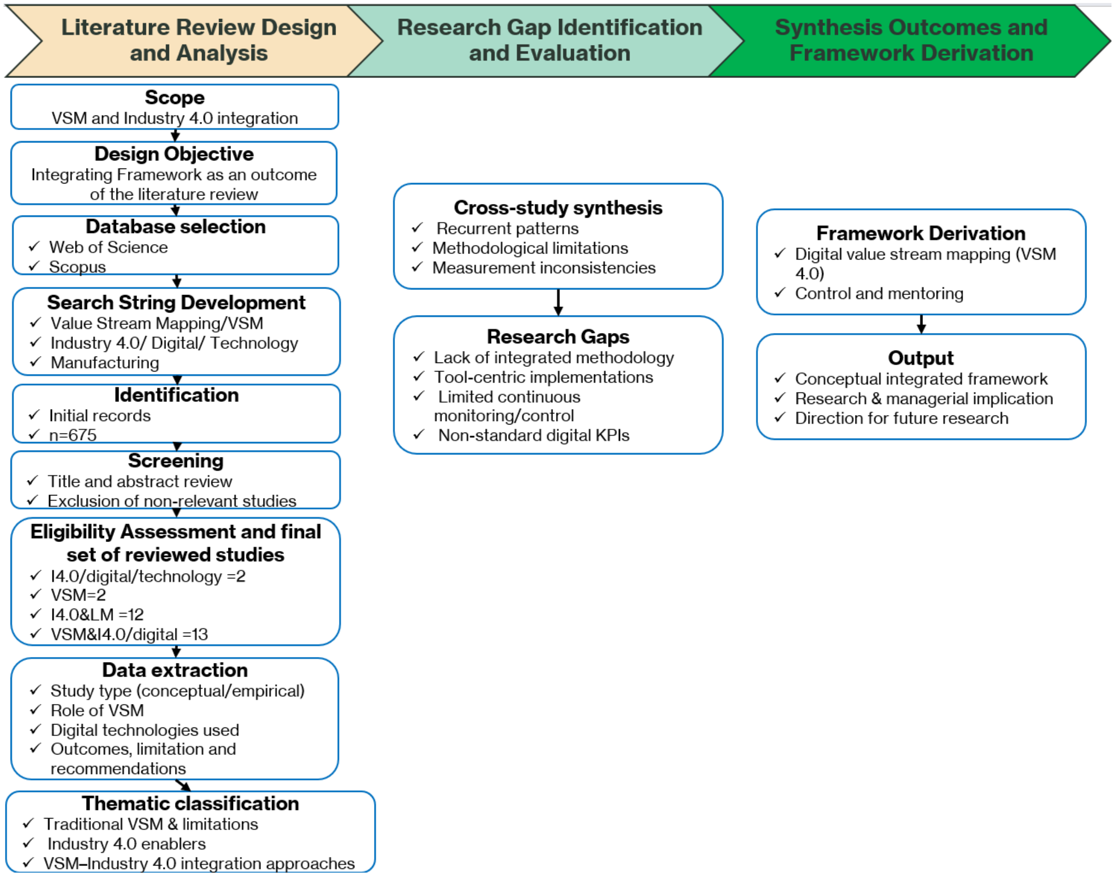

Figure 1. The methodology of the literature review illustrates how research gaps and the conceptual framework are derived from the reviewed studies.

3. Value Stream Mapping: Conceptual Foundations and Limitations

3.1 Value Stream Mapping in Lean Manufacturing

Value Stream Mapping (VSM) is a lean manufacturing technique that shows how materials and information move through production systems so that waste can be found and processes can be improved. Since its introduction in the lean literature, VSM has been primarily applied to describe current-state operations and to guide the design of future-state improvements (Hines and Rich 1997; Rother and Shook 2003). Providing a shared and structured view of production flows, which different functional groups can use during improvement initiatives.

Empirical studies indicate that VSM is particularly effective when applied in manufacturing environments with stable processes and predictable demand. Abdulmalek and Rajgopal (2007) demonstrated that VSM-based enhancement initiatives, particularly when augmented by simulation, can diminish lead time and work-in-process inventory. Similar findings have been reported in repetitive production settings, where VSM facilitates the identification of bottlenecks and non-value-adding activities.

In the majority of recorded applications, VSM functions as a periodic analytical instrument rather than a tool for ongoing operational management. As previously mentioned in this study, value stream maps usually show how a system works at a certain point and are only changed during planned improvement cycles. This pattern of use shows how VSM was meant to be used in lean practice, but it also shows when its limits become clear.

3.2 Structural and Operational Limitations of Traditional VSM

Despite its widespread use, several studies highlight limitations that restrict the applicability of traditional VSM in modern manufacturing systems. A commonly reported issue is the reliance on manually collected data, which represents system conditions at a single point in time. Such static representations limit the ability of VSM to reflect short-term variability, unplanned disturbances, and frequent operational changes (Forno et al. 2014).

The literature further indicates that the effort required to maintain and update value stream maps increases significantly in complex production environments. In systems characterized by high product variety, frequent changeovers, or volatile demand, repeated data collection and map revisions become time-consuming and may not keep pace with actual system behavior. Romero and Arce (2017) report that under these conditions, the diagnostic value of VSM decreases, as improvement decisions are often based on outdated information.

The display of information flows presents another limitation. While material flows are typically described in detail, information flows are often simplified and treated at an aggregate level. This restriction limits the usefulness of VSM in digitally enabled manufacturing environments, where real-time information exchange and data-driven coordination are essential. As a result, traditional VSM remains more suited to planning and improvement analysis than to continuous monitoring or control of value streams.

3.3 Methodological Extensions Beyond Traditional VSM

Recent studies increasingly address the limitations of traditional VSM by proposing methodological extensions that incorporate digital technologies. One such development is VSM 4.0 Plus, which extends conventional mapping by including technical aspects related to data generation, communication interfaces, data storage, and processing. By making these elements explicit, this approach improves the representation of information flows and supports closer alignment between value stream analysis and digital system design (Bega et al. 2023).

Other contributions propose multi-layer or multi-dimensional VSM frameworks that broaden the scope of value stream analysis beyond operational performance. These approaches integrate additional dimensions, such as environmental and social indicators, into the mapping process, allowing multiple performance objectives to be considered simultaneously (Heydarzade et al. 2025). Such extensions reflect a growing interest in more comprehensive representations of value streams.

However, the majority of these methodological developments concentrate on specific enhancements instead of offering an integrated structure for value stream monitoring and control. Existing approaches tend to address individual limitations of VSM in isolation, without systematically linking digital data acquisition, analysis, and operational decision-making. This fragmentation suggests the need for a coherent framework that connects digital technologies with continuous value stream monitoring and control, which forms the basis for the discussion in the following section.

4. Industry 4.0 and Digital Enablement of Value Streams

4.1 Industry 4.0 Capabilities Relevant to Value Stream Analysis

Industry 4.0 refers to the integration of digital technologies in manufacturing systems that enable connectivity, real-time data exchange, and decentralized decision-making. Rather than constituting a single technological solution, Industry 4.0 encompasses a set of enabling capabilities, including the Internet of Things (IoT), cyber-physical systems (CPS), cloud computing, and data analytics, that enable continuous data acquisition and improved visibility across production processes (Ghobakhloo 2018; Vaidya, Ambad, and Bhosle 2018)

From a value stream perspective, these capabilities address several limitations of traditional VSM identified in the literature. IoT-enabled sensors and CPS architectures allow production resources to continuously report operational states, while cloud-based platforms facilitate data aggregation across process stages. This provides the technical basis for observing material and information flows in real time rather than relying on periodically collected, manually recorded data.

Several studies examine the role of analytics and model-based techniques in extending value stream analysis. Digital twin and simulation-based approaches enable synchronized physical–digital representations of value streams, supporting continuous monitoring, scenario evaluation, and predictive analysis. These approaches extend VSM beyond static visualization toward more dynamic analysis (Frick and Metternich 2024; Wollert, Al-Aomar, and Behrendt 2024).

4.2 Industry 4.0 as an Enabler of Lean and Value Stream Practices

A growing body of literature highlights the conceptual alignment between Industry 4.0 technologies and lean manufacturing principles. Digital technologies can enhance lean practices by improving process transparency, reducing information delays, and enabling faster identification of deviations and bottlenecks across production systems. Several studies report that Industry 4.0 capabilities reinforce lean objectives such as waste reduction, flow stabilization, and responsiveness when applied within a structured improvement context (Buer, Strandhagen, and Chan 2018; Rosin et al. 2020).

At the same time, literature cautions against assuming that digitalization alone leads to improved lean performance. Without explicit integration mechanisms, Industry 4.0 initiatives often remain technology-driven rather than process-oriented. In value stream analysis, this frequently results in localized digital solutions that improve visibility at individual workstations but offer limited support for end-to-end flow optimization. Many implementations focus on workstation-level automation or data collection while neglecting coordination across the entire value stream.

This observation is consistent with findings that treat VSM and Industry 4.0 as parallel improvement initiatives rather than as components of a unified methodological system. As a consequence, the potential of digital technologies to transform value stream management remains underutilized in many industrial applications.

In many studies, VSM and Industry 4.0 are implemented as parallel initiatives rather than as elements of a unified methodological approach. As a result, digital technologies are often underutilized in value stream management. Several empirical studies further report that Industry 4.0 technologies act as enablers of lean practices by supporting flow transparency, coordination, and responsiveness across manufacturing systems (Ghobakhloo and Fathi 2020; Kamble et al. 2020; Narula et al. 2023; Sanders, Elangeswaran, and Wulfsberg 2016).

4.3 Implications for Value Stream Monitoring and Control

Beyond enhancing visibility and analytical capability, Industry 4.0 technologies enable value stream management to be treated as a continuous monitoring and control activity. Real-time data acquisition enables the tracking of flow-related indicators such as cycle time, work-in-process levels, and resource utilization across multiple process stages. When combined with analytics and simulation-based evaluation, these data support adaptive decision-making rather than periodic improvement interventions.

Recent research highlights the emergence of data-driven value stream evaluation approaches that leverage digital models and real-time data streams to compare alternative scenarios and assess system performance dynamically. Such approaches move VSM closer to an operational control mechanism by linking digital data flows with performance indicators and feedback loops (Kroeger et al. 2024). Similarly, studies on dynamic and hybrid simulation-based VSM demonstrate how digital representations of value streams can support near real-time shop-floor decision support and continuous improvement (Liu et al. 2025).

Despite these advances, literature remains fragmented. Most studies focus on individual technologies or localized applications and do not conceptualize value stream monitoring and control as an integrated function supported by Industry 4.0. This indicates the absence of a coherent framework that systematically connects digital capabilities with value stream management objectives. The following section synthesizes the literature on VSM–Industry 4.0 integration and identifies the research gaps that inform the proposed Digital Value Stream Mapping framework.

5. Integration of Value Stream Mapping and Industry 4.0: Literature Synthesis

The integration of Value Stream Mapping (VSM) with Industry 4.0 technologies has attracted increasing attention in recent years, particularly as manufacturers seek to overcome the static and snapshot-based nature of traditional value stream analysis. The reviewed literature reveals that integration efforts are motivated primarily by the need to enhance data availability, improve process visibility, and support more responsive decision-making across value streams.

However, rather than converging toward a unified methodological approach, existing studies do not converge toward a unified integration approach. Instead, they differ considerably in how integration is defined and operationalized.

Most contributions address specific technologies or isolated use cases, resulting in a fragmented body of work without a shared analytical structure. This fragmentation limits comparability across studies and reduces the transferability of proposed solutions.

5.1 Technology Centric Integration Approaches

A significant section of literature employs a technology-centric approach, utilizing Industry 4.0 tools to bolster specific VSM activities. Common examples include simulation-based analysis, IoT-enabled data collection, and agent-based or cyber-physical system implementations aimed at improving data accuracy and timeliness.

Simulation-based VSM methods are often used to test out improvement ideas before putting them into action. Abdulmalek and Rajgopal (2007) showed that simulation can enhance VSM by capturing system variability and allowing for quantitative evaluation. More recent studies extend this approach by integrating discrete-event and hybrid simulation models with real-time data streams, allowing dynamic assessment of value stream performance (Wollert, Al-Aomar, and Behrendt 2024).

Similarly, IoT and cyber-physical systems are commonly applied to automate data collection for VSM. Using sensors to collect data lessens the need for manual observation and makes it easier to update value stream information more often (Frick and Metternich 2024; Hartmann et al. 2018). However, these implementations typically enhance data input without altering the fundamental role of VSM within the manufacturing system.

5.2 Methodological Integration and Digital VSM Concepts

Beyond technology-centric implementations, several studies attempt to redefine VSM itself by embedding digital capabilities into the mapping methodology. These efforts are commonly referred to as Digital VSM, VSM 4.0, or Value Stream Management 4.0. Such approaches extend traditional VSM by incorporating real-time data flows, digital representations, and enhanced information structures.

Meudt et al. (2017) introduced VSM 4.0 as a conceptual extension that incorporates Industry 4.0 elements while maintaining alignment with lean principles. Subsequent work expanded this concept by specifying technical properties related to data points, communication interfaces, and data processing, as demonstrated in VSM 4.0 Plus (Bega et al. 2023). These developments improve the representation of digital information flows and strengthen the connection between value stream analysis and digital system architecture. Further research has implemented digital VSM concepts via simulation-based and agent-based methodologies. For instance, Trebuna et al. (2019) utilized digital VSM with industrial simulation software, whereas Huang et al. (2019) and de Paula Ferreira et al. (2022) suggested agent-based systems to facilitate dynamic value stream mapping in Industry 4.0 contexts.

Recent studies' contributions propose multi-layer and multi-variable VSM frameworks that integrate operational performance with additional dimensions such as environmental and social indicators. These approaches reflect efforts to broaden the scope of value stream analysis and address multiple performance objectives within a single framework (Heydarzade et al. 2025). In most cases, however, these frameworks remain conceptual and are not applied as part of continuous operational monitoring or control systems.

5.3 Integration Outcomes and Limitations

Although the reviewed studies report benefits from integrating VSM with Industry 4.0 technologies, several recurring limitations emerge from the synthesis. First, most integration efforts remain tool-centric, focusing on enhancing specific VSM activities rather than redefining VSM as an end-to-end management mechanism. As a result, digital solutions often operate in isolation, limiting their impact on overall value stream performance.

Second, empirical evidence is dominated by single-case studies and context-specific applications. While these studies provide useful insights, they limit generalizability and hinder the development of transferable integration guidelines. In addition, performance assessment varies considerably across studies, with little consistency in the selection of digital KPIs for continuous value stream monitoring.

Finally, despite the availability of real-time data and advanced analytics, few studies address value stream control as a continuous function. Most approaches emphasize diagnostic analysis and scenario evaluation, while explicit closed-loop mechanisms that connect monitoring, decision-making, and execution remain largely absent.

6. Discussion: Research Gaps and Implications of the Review

The literature synthesis indicates that, despite increasing research interest in integrating Value Stream Mapping (VSM) with Industry 4.0 technologies, several recurring gaps remain unresolved. Conceptual, methodological, and empirical studies consistently reveal these gaps, reflecting limitations in the current linkage between digital technologies and value stream analysis.

First, current research lacks a coherent integration framework that incorporates digital technologies throughout the entire value stream mapping process. Most contributions apply Industry 4.0 tools to specific tasks, such as data collection or scenario evaluation, without defining how these tools interact within a unified value stream analysis and management structure. Consequently, VSM is still applied mainly as a diagnostic representation rather than as a mechanism for continuous value stream management.

Second, much of the literature adopts a tool-centric perspective, focusing on individual technologies such as simulation, IoT, or digital twins considered in isolation. While such studies demonstrate localized benefits, they provide limited guidance on how multiple digital technologies should be coordinated within a coherent value stream architecture. The lack of this coordination limits scalability and makes it harder to use proposed solutions in different production settings.

Third, the empirical basis of Digital VSM research remains limited. Most empirical contributions rely on single-case studies or context-specific applications. Although these studies offer useful insights, they restrict generalization and hinder the development of transferable implementation principles. In addition, performance evaluation practices vary considerably, with little consistency in the selection of digital performance indicators suitable for continuous value stream monitoring and comparison.

Finally, despite the availability of real-time data and advanced analytics, value stream control is rarely addressed as a continuous function. Most studies remain focused on periodic analysis and improvement planning, while closed-loop mechanisms that link monitoring, decision-making, and execution are largely absent. This gap reflects a mismatch between the capabilities offered by digital manufacturing technologies and the traditional application scope of VSM.

6.1 Implications for Research

From a research standpoint, these gaps indicate the necessity to reevaluate the function of VSM within digitally enabled manufacturing systems. Instead of viewing VSM as a static visualization tool enhanced by digital technologies, future research should adopt methodologies that clearly delineate how digital capabilities facilitate data acquisition, analysis, decision-making, and feedback throughout the entire value stream.

Comparative and multi-case research designs that examine Digital VSM implementations across different industrial settings are also necessary for further investigation. Such studies can support the identification of transferable design principles and contribute to the development of more consistent digital performance indicators for value stream monitoring and control.

Furthermore, we need to focus more on examining the interplay between lean principles and digital control mechanisms. Understanding how real-time monitoring, analytics, and feedback loops can be aligned with lean objectives is essential to ensure that digitalization reinforces, rather than undermines, established value stream improvement practices.

6.2 Implications for Practice

For practitioners, the review indicates that adopting Industry 4.0 technologies without a structured integration approach may yield limited improvements in value stream performance. Digital tools implemented in isolation tend to enhance local visibility while offering limited support for end-to-end flow coordination.

The findings suggest that the effective digitalization of value streams requires alignment between digital initiatives and value stream objectives. Data collection, analytical capabilities, and decision-support mechanisms need to be designed with explicit consideration of how they contribute to continuous monitoring and coordinated control across process stages. Without this alignment, investments in digital technologies risk remaining confined to localized improvements rather than supporting value stream management at the system level.

6.3 Need for Framework Development

Overall, the discussion demonstrates that while literature provides substantial evidence of the potential benefits of integrating VSM with Industry 4.0 technologies, current approaches remain fragmented and methodologically incomplete. The identified research gaps underscore the need for a coherent framework that systematically connects digital capabilities with value stream analysis, monitoring, and control.

These insights directly inform the development of the conceptual framework presented in the following section. The proposed framework is derived from the synthesis of the reviewed literature and aims to address the identified gaps by providing a structured approach to Digital Value Stream Mapping that supports continuous, data-driven value stream management.

7. Conceptual Framework for Digital Value Stream Mapping

The review and synthesis presented in the preceding sections show that current attempts to integrate Value Stream Mapping (VSM) with Industry 4.0 technologies remain largely fragmented. Existing approaches typically apply digital tools to selected value stream activities without defining how data acquisition, analysis, and control functions are connected within a single value stream management logic. As a result, VSM continues to be used mainly for diagnostic and planning purposes, despite the availability of technologies that support continuous data collection and analysis.

Based on the research gaps discussed in Section 6, this study derives a conceptual framework for Digital Value Stream Mapping (DVSM) that links lean value stream logic with Industry 4.0 capabilities. The framework is presented as a conceptual structure rather than as a technical system design. Its purpose is to clarify how digital technologies can be organized to support value stream analysis, monitoring, and control in an integrated manner, consistent with patterns and limitations identified in the reviewed literature.

7.1 Framework Structure and Core Components

The proposed framework conceptualizes Digital Value Stream Mapping as a multi-layered system composed of four interrelated components:

- (i) value stream structure,
- (ii) digital data acquisition,
- (iii) analytical and evaluation layer,
- (iv) monitoring and control mechanisms.

These components represent functional layers that interact within a closed-loop value stream management process. Together, they describe how digital technologies can support continuous visibility, analysis, and decision-making while preserving the core principles of lean value stream analysis. Figure 2 illustrates the conceptual framework for Digital Value Stream Mapping (DVSM). The framework is organized around four interrelated components: the value stream structure, digital data acquisition, analytical and evaluation capabilities, and monitoring and control mechanisms. The value stream structure forms the core of the framework, representing the processes and flows defined through lean value stream analysis. Digital data acquisition supports the continuous collection of operational data across the value stream and provides inputs to the analytical and evaluation layer. This layer enables the assessment of value stream performance and the evaluation of alternative scenarios using data-driven methods. Monitoring and control mechanisms link analytical outputs to operational decision-making by enabling feedback actions that influence the value stream structure. The interactions between components illustrate a closed-loop value stream management process, where data collection, analysis, and control are continuously interconnected.

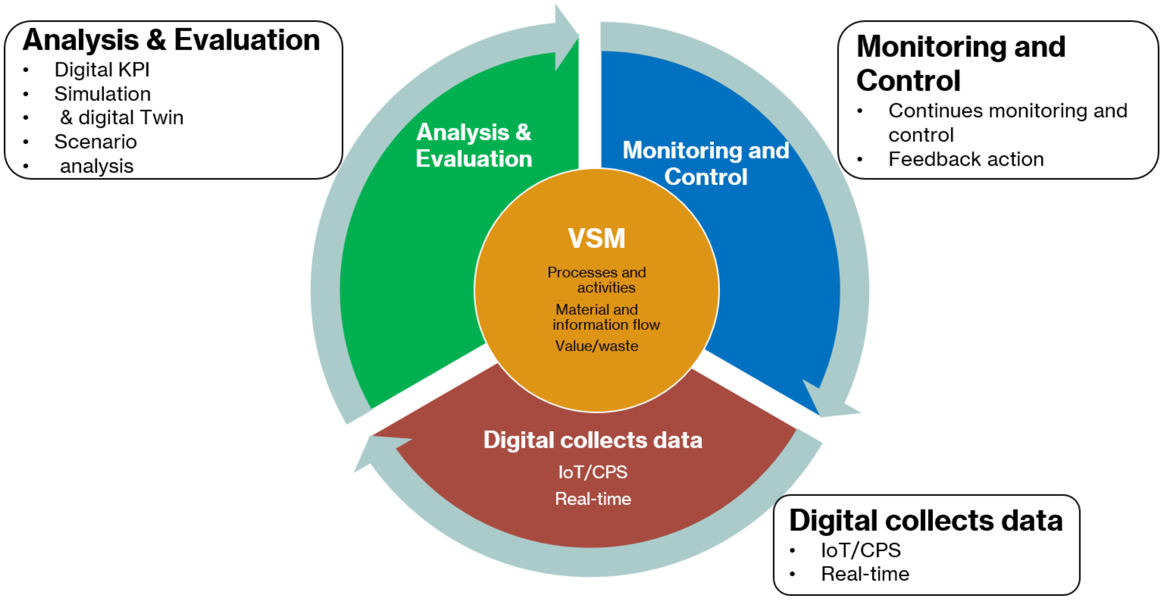

Figure 2. Proposal conceptual framework

7.1.1 Value Stream Structure

The value stream structure forms the foundation of the framework and corresponds to the traditional representation of processes, material flows, and information flows within VSM. This component preserves the lean focus on flow orientation, waste identification, and value creation. It provides a structured reference for understanding how activities are connected across the production system. Within the proposed framework, the value stream structure functions as a conceptual reference model that is informed by digital data. Rather than representing a static snapshot, it serves as the basis upon which data-driven analysis and monitoring activities are applied. This preserves the analytical logic of VSM while enabling more frequent and informed evaluation of value stream performance.

7.1.2 Digital Data Acquisition

The second component of the framework consists of the digital data acquisition layer enabled by Industry 4.0 technologies. This layer integrates IoT devices, cyber-physical systems, and digital interfaces to collect real-time operational data from production resources. Data related to process states, cycle times, inventory levels, and resource utilization are continuously captured and transmitted across the value stream.

By automating data collection, this layer addresses one of the primary limitations of traditional VSM. its reliance on manually collected, time-specific data and establishes the technical foundation for continuous value stream visibility.

7.1.3 Analytical and Evaluation

The analytical and evaluation layer transforms raw operational data into actionable insights. Drawing on the reviewed literature, this layer incorporates data analytics, simulation, and digital twin capabilities to support the evaluation of current performance and the exploration of alternative scenarios.

Within this layer, digital performance indicators are calculated to assess flow efficiency, bottleneck behavior, and variability across the value stream. Unlike conventional VSM metrics, these indicators are updated dynamically, enabling comparative analysis and supporting data-driven decision-making. This component directly responds to the identified gap concerning the absence of standardized digital KPIs and evaluation mechanisms in existing Digital VSM approaches.

7.1.4 Monitoring and Control Mechanisms
The final component of the framework introduces monitoring and control mechanisms that connect value stream analysis with operational decision-making. While feedback mechanisms enable the consideration and implementation of corrective actions, continuous monitoring supports the detection of deviations from desired performance levels.

Rather than replacing lean improvement practices, this component enhances established lean improvement practices by facilitating more timely decision-making. In this way, the framework repositions VSM from a periodic diagnostic tool to an ongoing management instrument capable of supporting continuous improvement in digitally enabled manufacturing environments.

7.2 Interactions Between Framework Components
The framework emphasizes interaction between components rather than their isolated application. Data acquired from production processes feed the analytical layer, which supports monitoring and control actions that influence the underlying value stream structure. This interaction forms a closed-loop process that connects observation, analysis, and action.

By organizing digital capabilities around the value stream structure and explicitly linking them through feedback mechanisms, the framework supports a shift from linear, snapshot-based analysis toward continuous value stream management. This closed-loop view fits with the needs of modern manufacturing systems, which are known for their variability, interconnectivity, and real-time data availability.

7.3 Expected Contributions and Applicability
The proposed conceptual framework enhances literature by elucidating the function of digital technologies in value stream management and by tackling the limitations recognized in previous research. For researchers, the framework offers a basis for future empirical validation and comparative analysis. For practitioners, it offers a conceptual framework for aligning digital initiatives with value stream goals and for creating Digital VSM implementations that enable ongoing monitoring and control.

Importantly, the framework is intended to be adaptable across different manufacturing contexts rather than confined to a specific technology or industry. Its conceptual nature allows it to be extended and refined as digital manufacturing technologies continue to evolve.

The framework derived in this section synthesizes the insights gained from the reviewed literature and addresses the research gaps identified in Section 6. The concluding section summarizes the key contributions of the study and outlines directions for future research aimed at empirically validating and extending the proposed Digital Value Stream Mapping framework.

8. Conclusions and Future Research
8.1 Conclusion
This study examined the integration of Value Stream Mapping (VSM) and Industry 4.0 technologies through a systematic review and synthesis of the current literature. The analysis verifies that VSM is a recognized lean methodology for examining material and information flows; however, its traditional use is predominantly confined to static and periodic analysis. In manufacturing environments characterized by increasing complexity and digitalization, this application scope constrains the role of VSM in supporting timely and data-informed decision-making.

The reviewed literature shows that Industry 4.0 technologies, such as simulation, IoT, digital twins, and data analytics are increasingly applied to enhance value stream analysis. However, these efforts typically fragment and focus on specific tools or localized use cases. As a result, digital solutions often improve data availability or local visibility without providing an integrated structure for continuous value stream monitoring, evaluation, and control.

To address these limitations, this study synthesized existing research and derived a conceptual framework for Digital Value Stream Mapping (DVSM). The framework links lean value stream logic with digital data acquisition, analytical evaluation, and monitoring and control mechanisms within a unified conceptual structure. Rather than proposing a prescriptive system design, the framework clarifies how VSM can evolve from a predominantly diagnostic tool into a continuous, data-driven approach to managing value streams.

The main contribution of this study lies in clarifying the conceptual role of digital technologies in value stream management and in providing a structured perspective that addresses recurring gaps identified in the literature. By grounding the framework in a comprehensive review and synthesis, the study contributes to both the lean manufacturing and Industry 4.0 research domains.

8.2 Implications of the Study

From an academic perspective, this study consolidates dispersed contributions on Digital VSM and discusses the importance of integrated methodological approaches that move beyond tool-centric implementations. The proposed framework provides a conceptual reference for future empirical studies and comparative analyses examining how digital technologies aid in monitoring value streams and controlling them.

From a practical perspective, the findings indicate that adopting Industry 4.0 technologies in isolation is unlikely to deliver sustained improvements in value stream performance. Digital initiatives are more likely to support system-level improvement when they are aligned with value stream objectives and designed to enable continuous data collection, analysis, and coordinated decision-making across process stages.

8.3 Future Research Directions

The conceptual nature of the proposed framework points to several directions for future research. Empirical validation is required to examine how Digital VSM operates across different manufacturing contexts and organizational settings. Multiple case studies could reveal how continuous monitoring and control methods affect value stream performance over time.

Further research is also needed to develop and validate digital performance indicators suitable for continuous value stream monitoring and comparison. Establishing such indicators would support both empirical evaluation and practical implementation of Digital VSM.

In addition, future studies may explore the integration of advanced analytics, artificial intelligence, and adaptive control mechanisms within Digital VSM frameworks. Such work could examine how predictive and prescriptive models contribute to proactive value stream management. Finally, the framework may be extended to incorporate sustainability-related dimensions, enabling multi-dimensional value stream analysis aligned with emerging manufacturing and sustainability objectives.

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