

Review

Optimizing Project Management through Lean Six Sigma and Industry 4.0: A Review, Gap Analysis, and Conceptual Mapping for Project Management 4.0

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Abstract: Modern projects operate in environments of increasing complexity, uncertainty, and digital transformation, exposing the limitations of traditional project management. Projects now face dynamic stakeholder demands, complex interdependencies, and intense performance pressures, requiring integrated, adaptive, and data-driven management approaches. While Lean Six Sigma (LSS) provides structured methods for process efficiency, waste reduction, and variability control, Industry 4.0 technologies—including AI, IoT, digital twins, RPA, and cloud platforms—enable real-time data, predictive analytics, and intelligent decision support. Current research often examines these domains separately, resulting in fragmented insights and limited practical guidance. To address this gap, this study proposes Project Management 4.0 (PM 4.0), an integrative framework that aligns LSS principles, tools, and DMAIC phases with Industry 4.0 technologies across the project lifecycle. PM 4.0 enables adaptive, value-focused project execution, embedding continuous improvement, strategic alignment, and performance transparency. By combining methodological rigor with digital intelligence, it enhances planning, execution, monitoring, and control, improving efficiency, agility, decision quality, and resilience. This research advances PM 4.0 theory and provides actionable guidance for managers, practitioners, and researchers seeking intelligent, high-performing project management systems. It also identifies future research directions, including empirical validation, human-centric digital integration, and intelligent governance.

Keywords: Project Management Optimization; Project Management 4.0; Lean Six Sigma; Industry 4.0; Digital Transformation; Agile Project Management; Project Performance Improvement

1. Introduction

Project management (PM) is essential for the effective planning, execution, and delivery of projects across industries. Contemporary projects are increasingly complex due to globalization, rapid digital transformation, and interorganizational interdependencies, resulting in heightened uncertainty, dynamic stakeholder expectations, compressed timelines, and intensified performance pressures. These challenges expose the limitations of traditional, linear PM approaches, which often lack flexibility, adaptive mechanisms, and real-time intelligence [1]. To address these limitations, organizations are adopting Lean Six Sigma (LSS), a structured, data-driven methodology that enhances operational efficiency, reduces process variability, and fosters continuous improvement [2,3]. LSS provides a systematic framework for identifying inefficiencies, improving quality, and optimizing project outcomes. Simultaneously, Industry 4.0 (I 4.0) technologies—including artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), digital twins (DTs), and cloud computing—enable predictive insights, automated workflows, and

enhanced collaboration, transforming project management practices [4–6].

Building Information Modeling (BIM) complements this integration by offering digital, multidimensional representations of a building’s physical and functional characteristics throughout its lifecycle. By consolidating design, construction, and operational data into a shared digital model, BIM facilitates collaboration among architects, engineers, contractors, and facility managers, enhancing visualization, reducing errors, optimizing resource allocation, and ensuring coordination from planning through operations. Widely applied in architecture, engineering, and construction (AEC) projects, BIM supports efficiency, sustainability, and overall project performance [7–9]. Project management encompasses structured, interrelated functions designed to achieve objectives while balancing scope, time, cost, quality, and risk. Core activities—planning, organizing, executing, monitoring, and controlling—are supported by governance frameworks, tools, and methodologies aligned with organizational strategy. Modern approaches increasingly integrate agile principles, digital technologies, and continuous improvement practices, enabling predictive insights, adaptive planning, and real-time decision-making. **Table 1** presents a holistic framework linking strategic, operational, and learning dimensions across governance, planning, execution, monitoring, and organizational learning, positioning PM as a value-driven, adaptive, and continuously improving capability [10–12].

Table 1. Project Management Functions Framework.

#	Functional Group	Category	Core Functions	Strategic Objective
1	Strategic Governance & Alignment	Initiation & Governance	Business case development, stakeholder analysis, charter definition, and governance establishment	Strategic alignment and accountable governance
2	Strategic Governance & Alignment	Value, Scope & Requirements	Scope definition, requirements management, value prioritization, and success metrics	Value delivery within a controlled scope
3	Planning & System Design	Schedule & Workflow	WBS development, activity sequencing, dependency mapping, and milestone definition	Predictable and efficient project execution
4	Planning & System Design	Cost, Resource & Capacity	Cost estimation and control, budgeting, resource allocation, capacity balancing	Cost efficiency and optimal resource utilization
5	Execution & Coordination	Team & Communication	Team leadership, cross-functional coordination, communication management, stakeholder engagement	Coordinated collaboration and execution alignment
6	Execution & Coordination	Quality & Process	Quality planning and control, process standardization, and waste elimination	High-quality and efficient delivery
7	Monitoring, Control & Adaptation	Performance Control	KPI monitoring, earned value analysis, variance control, and corrective actions	Performance stability and timely correction
8	Monitoring, Control & Adaptation	Risk & Change	Risk identification and assessment, mitigation planning, and change control	Reduced uncertainty and enhanced adaptability
9	Learning & Continuous Improvement	Knowledge & Improvement	Lessons learned, capture, knowledge sharing, process optimization	Continuous improvement and organizational learning

1.1. Lean Six Sigma in Project Management

Lean Six Sigma combines Lean principles, which eliminate non-value-adding activities, with Six Sigma methodologies, which reduce variability and enhance quality. Within PM, LSS improves execution, optimizes resource utilization, and increases outcome reliability through structured problem-solving, continuous improvement, and proactive risk management. **Table 2** illustrates an LSS-driven PM framework across six clusters—Strategic Governance & Alignment, Planning & System Design, Execution & Coordination, Monitoring & Adaptation, Learning & Continuous Improvement, and Closure & Value Realization—demonstrating how tools such as SIPOC, VOC, CTQ, Process Mapping, FMEA, DMAIC, SPC, Kaizen, and PDCA drive efficiency, quality, and value [13–15]. Integration with I 4.0 technologies further enhances real-time monitoring, predictive planning, and adaptive control, strengthening agility, responsiveness, and resilience [16–18].

Table 2. Lean Six Sigma-Driven Project Management Framework.

#	Cluster/Group	Purpose/Focus	Representative LSS Tools	PM Applications/Impact
1	Strategic Governance & Alignment	Align projects with organizational strategy and stakeholders	SIPOC, VOC, CTQ	Define objectives, clarify requirements, ensure strategic alignment
2	Planning & System Design	Design workflows, schedules, and resource plans	Process Mapping, FMEA, VSM, Control Charts	Optimize processes, mitigate risks, improve scheduling and resource utilization
3	Execution & Coordination	Execute project plans efficiently while maintaining quality	5S, Standard Work, Kaizen, Gemba	Enhance team collaboration, reduce waste and variation, ensure consistent quality
4	Monitoring, Control & Adaptation	Monitor performance, manage deviations, and address change	DMAIC, SPC, Pareto, Root Cause Analysis	Enable timely corrective actions and effective risk management
5	Learning & Continuous Improvement	Capture knowledge and refine processes	PDCA, Kaizen, Benchmarking, 5 Whys	Institutionalize lessons learned and drive continuous improvement

Table 2. Cont.

#	Cluster/Group	Purpose/Focus	Representative LSS Tools	PM Applications/Impact
6	Closure & Value Realization	Confirm completion and realize project benefits	Control Charts, KPI Analysis, Lessons Learned	Ensure deliverables, validate benefits, and sustain project value

1.2. Industry 4.0 Technologies in Project Management

I 4.0 technologies establish connected, intelligent, and data-driven project ecosystems that enable predictive decision-making, automation, and enhanced collaboration [19–21]. **Table 3** presents seven technology groups and their applications—Data & Analytics, Digital Twin & Simulation, IoT & Sensor Networks, Cloud & Collaboration Platforms, Automation & Robotics, AR/VR, and Blockchain & Cybersecurity—demonstrating how these tools improve efficiency, quality, monitoring, and governance across the project lifecycle [22–24]. Collectively, these technologies enable scenario-based planning, predictive management, and adaptive decision-making, transforming traditional PM into an intelligent, responsive, and data-driven system [25–28].

Table 3. Industry 4.0 Technology Groups for Project Management (Adjusted).

#	Technology Group	Key Technologies	PM Capabilities	Representative PM Applications
1	Data & Analytics	AI, Machine Learning, Big Data, Predictive Analytics	Real-time insights, predictive decisions	Forecast risks, monitor performance, optimize resources
2	Digital Twin & Simulation	Digital Twins, 3D Modeling, Simulation Software	Virtual modeling, scenario testing, process optimization	Simulate workflows, test schedules, optimize resources
3	IoT & Sensor Networks	Industrial IoT, Smart Sensors, RFID	Real-time tracking, automated monitoring	Track assets, monitor progress, enable proactive actions
4	Cloud & Collaboration	Cloud Computing, SaaS, Collaboration Tools	Centralized access, remote coordination	Share documents, manage dashboards, coordinate teams
5	Automation & Robotics	RPA, AI-driven Automation, Autonomous Equipment	Task automation, efficiency improvement	Automate tasks, update schedules, generate reports, ensure quality
6	AR/VR	AR/VR Platforms, Mixed Reality Devices	Immersive visualization, virtual planning	Conduct virtual inspections, immersive planning, interactive walkthroughs
7	Blockchain & Cybersecurity	Blockchain, Smart Contracts, Cybersecurity Tools	Data integrity, secure transactions	Secure contracts, maintain audit trails, and ensure tamper-proof records

1.3. Integrating LSS and Industry 4.0: Towards Project Management 4.0

While LSS and I 4.0 individually enhance project outcomes, research on their combined application remains limited. The emerging Project Management 4.0 (PM 4.0) paradigm integrates LSS methodologies with I 4.0 technologies to create agile, resilient, and data-driven systems that enhance efficiency, adaptability, and value creation across the project lifecycle. This integration combines structured process discipline with digital intelligence, predictive analytics, and real-time adaptability. LSS tools—such as DMAIC, FMEA, and SPC—work synergistically with IoT, AI/ML, digital twins, RPA, AR/VR, and cloud platforms to enable continuous monitoring, predictive risk assessment, scenario-based planning, automated workflows, and collaborative visualization. Together, they form a data-driven, adaptive PM ecosystem that improves efficiency, quality, stakeholder satisfaction, and organizational learning, transforming traditional linear management into a fully integrated LSS + I 4.0 system focused on predictive capability and optimized value creation [29–31]. **Figures 1** and **2** illustrate this framework. **Figure 1** shows the progression from traditional PM to a fully integrated LSS + I 4.0 ecosystem across eight milestones, emphasizing efficiency, predictive insight, and continuous improvement. **Figure 2** places LSS methodologies at the center, surrounded by I 4.0 technologies, forming a circular project lifecycle with feedback loops that support adaptive learning, predictive management, and value-driven outcomes.

1.4. Problem Statement

Despite the recognized benefits of LSS and I 4.0, few studies systematically examine their combined application in project management. Most research addresses these domains independently, resulting in fragmented frameworks, inconsistent implementation strategies, and limited guidance for applying both process improvement and digital technologies across the project lifecycle. This gap prevents organizations from fully leveraging predictive analytics, real-time monitoring, and scenario-based planning alongside structured continuous improvement methodologies.

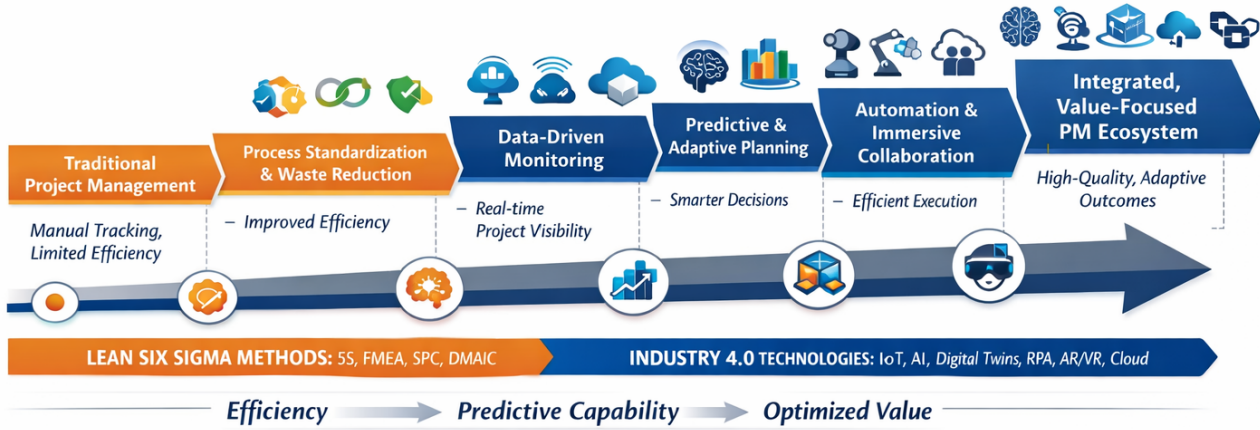


Figure 1. Milestone Evolution Map of Project Management Integrating Lean Six Sigma and Industry 4.0.

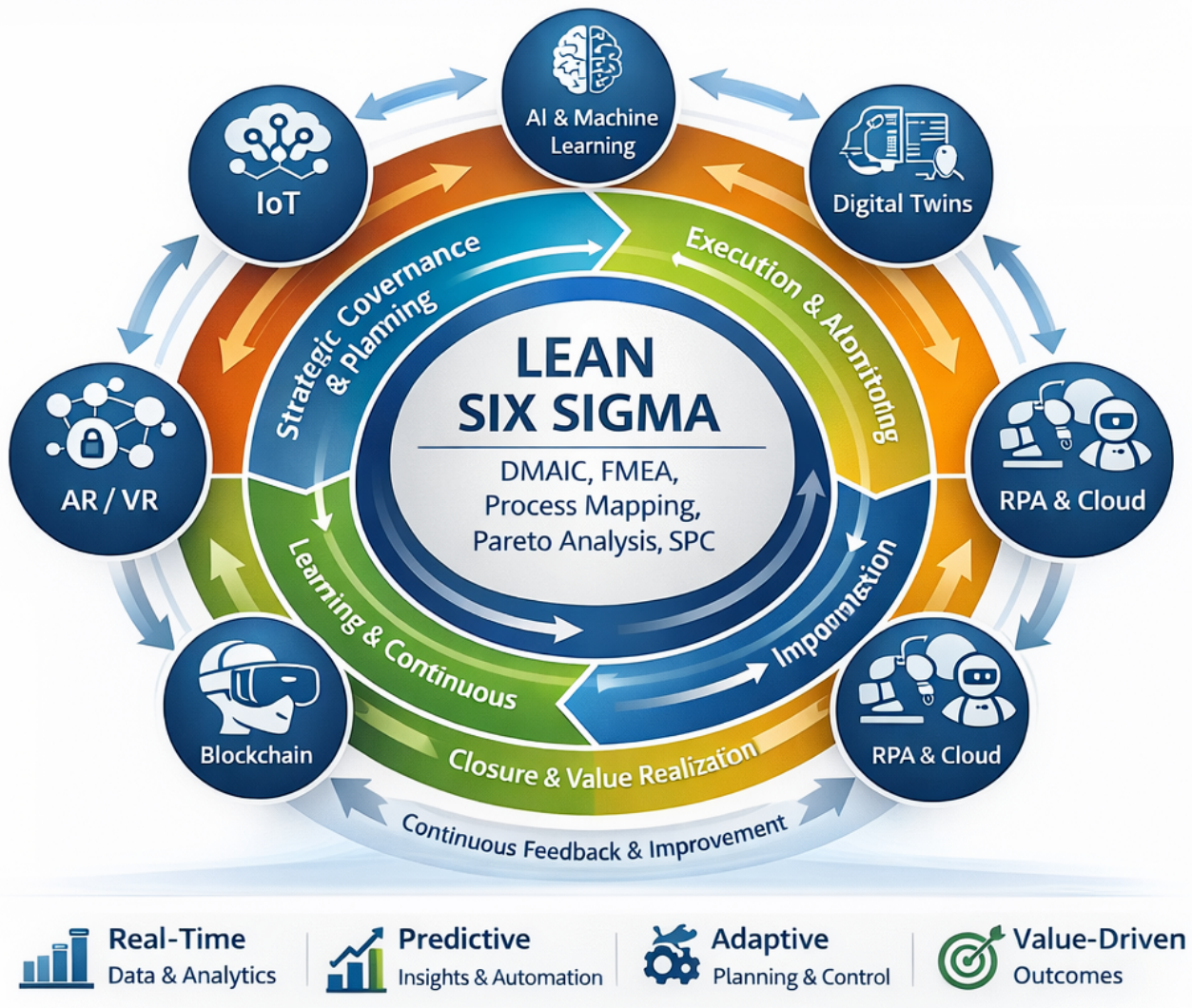


Figure 2. Integrated LSS and Industry 4.0 Framework for Optimized PM.

As a result, project managers struggle to develop adaptive, data-driven, and value-focused PM systems, partic-

ularly in complex environments with interdependent processes, diverse stakeholders, and rapidly evolving requirements. The lack of integration between LSS tools—such as DMAIC, FMEA, and SPC—and I 4.0 technologies—such as AI, IoT, digital twins, and cloud platforms—reduces opportunities for improved decision-making, operational efficiency, and stakeholder satisfaction. Moreover, few studies address organizational challenges such as knowledge transfer, learning, and stakeholder engagement, which are essential for sustaining high performance.

These gaps highlight the need for a holistic, integrative framework—Project Management 4.0 (PM 4.0)—that unifies LSS methodologies and I 4.0 technologies into a coherent ecosystem. Such a framework can guide practitioners in building intelligent, resilient, and high-performing project management systems capable of navigating the complexities and uncertainties of contemporary projects.

1.5. Study Objectives and Contributions

This study develops a comprehensive Project Management 4.0 (PM 4.0) framework that integrates LSS methodologies with I 4.0 technologies across the project lifecycle. The objectives are to examine the theoretical and practical intersections of LSS and I 4.0, identify challenges and research gaps, propose an actionable, adaptive, and data-driven PM 4.0 framework, and provide practical guidance for managers, practitioners, and researchers.

By bridging theory and practice, this research contributes to project management knowledge and establishes a foundation for sustainable, high-performing, and digitally empowered systems. The PM 4.0 framework enhances operational efficiency, decision quality, continuous learning, adaptability, and resilience.

The paper is structured as follows: Section 2 presents the literature review; Section 3 identifies challenges and research gaps; Section 4 introduces the conceptual framework; and Section 5 concludes with key findings and future research directions.

2. Literature Review

This study comprehensively reviews peer-reviewed articles published between 2011 and 2025, indexed in Scopus, Web of Science, and ScienceDirect, focusing on project management optimization through Lean Six Sigma (LSS), Industry 4.0 (I 4.0) technologies, and their integration within Project Management 4.0 (PM 4.0). The review synthesizes theoretical and empirical insights, highlighting trends, enablers, challenges, and research gaps. By bridging operations management, quality management, digital transformation, and project management literature, it provides a solid foundation for developing an integrated PM 4.0 framework.

The review is organized into two main subsections: (1) Lean Six Sigma in project management, and (2) Industry 4.0 technologies in project management. This structure enables a comprehensive understanding of the evolution of project management practices and the emergence of digitally empowered, high-performance project management systems.

2.1. Lean Six Sigma in Project Management

Lean Six Sigma (LSS) integrates Lean principles, which eliminate waste, with Six Sigma methodologies, which reduce variability and improve quality. Lean emphasizes maximizing customer value by removing non-value-adding activities such as delays, rework, defects, and material inefficiencies. Six Sigma provides a structured, data-driven framework for process stability, predictive analysis, and evidence-based decision-making. Together, LSS fosters continuous improvement, organizational learning, and long-term operational excellence [32–35]. Within project management, LSS tools—including DMAIC, FMEA, Value Stream Mapping, Pareto analysis, and Statistical Process Control (SPC)—enable detection of inefficiencies, anticipation of failures, and corrective actions, enhancing process visualization, decision-making, and performance [36–38].

LSS has demonstrated effectiveness across sectors. In manufacturing, pharmaceutical companies applying LSS during COVID-19 reduced downtime and achieved savings exceeding USD 500,000 [39]. In construction, DMAIC-driven projects minimized schedule overruns, while IT organizations improved defect detection and reduced rework. Healthcare systems optimized patient flow, reduced waiting times, improved service reliability, and lowered error rates [40,41]. In developing countries, implementation is hindered by limited resources, infrastructure constraints, cultural differences, leadership gaps, and resistance to change [42]. Context-specific adaptations, such as simplified DMAIC frameworks and low-cost Lean tools like 5S and Kaizen, have proven effective in India and

Vietnam, providing practical, cost-efficient solutions that enhance employee engagement without significant investment [43–45].

Successful LSS adoption relies on strategic alignment, leadership commitment, employee engagement, cross-functional collaboration, and systematic use of structured tools [11,12]. Tailored frameworks outperform generic approaches by addressing contextual realities, while dynamic capabilities allow organizations to sense opportunities, adapt processes, and sustain performance in volatile environments [40,46]. Organizational readiness, cultural alignment, comprehensive training, and long-term strategic focus are essential; without these, LSS initiatives risk fragmented or short-term improvements.

Sustainable Lean Six Sigma (SLSS) extends LSS by integrating environmental, social, and economic considerations. SLSS enhances efficiency and quality while reducing waste, emissions, and resource use, promoting continuous improvement that is economically, environmentally, and socially responsible [47,48]. A review of 342 Scopus-indexed articles (2001–2023) indicates a shift toward data-driven approaches that combine mathematical modeling, multi-criteria decision-making (MCDM) techniques, and I 4.0 technologies, with adoption strongest in manufacturing and healthcare, while service sectors remain underexplored [49]. SLSS strengthens resilience during disruptions, such as COVID-19, and builds stakeholder trust through regulatory compliance and social responsibility [50,51].

Green Lean Six Sigma (GLSS) integrates environmental management with LSS to improve efficiency and quality while minimizing ecological impact. By combining Lean waste elimination, Six Sigma defect reduction, and sustainability metrics—such as energy consumption, carbon footprint, water use, and recycling—GLSS enables eco-efficient operations across value chains. Widely applied in manufacturing, supply chains, and project management, GLSS reduces costs, optimizes resource use, ensures regulatory compliance, and enhances corporate reputation [52–56].

In construction, lean practices are crucial for efficiency, waste reduction, and improved outcomes. Aravindh et al. [57] identified 36 types of waste in Indian projects, highlighting labor excess and inefficient material handling as major contributors to delays and cost overruns. Waiting time and defects had the largest impact, while “making-do” occurred most frequently. Babalola et al. [58] identified 32 lean practices across design, planning, site management, and health and safety, with the Last Planner System and Just-in-Time being the most adopted. Durai-Aravindh et al. [59] applied AHP to select root cause analysis as the most effective lean tool based on time, cost, quality, and ease of use. Despite progress, research remains concentrated in the UK and the USA, highlighting the need for context-specific studies in countries such as India [60]. Garcés et al. [61] and Wattana et al. [62] further confirmed that lean practices improve efficiency, shorten delivery times, reduce waste, and enhance sustainability, particularly in resource-constrained environments.

Construction project delays often arise from technical, organizational, and human factors. Agyekum-Mensah and Knight [63] identified 32 delay themes in the London Olympic 2012 project, including competence gaps, poor commercial decisions, excessive health and safety restrictions, inadequate risk management, and inefficient logistics planning. Aravindh et al. [57] linked waiting time and defects to delays, while Wattana et al. [62] emphasized material waste reduction as key to improving performance. These findings underscore the importance of integrating lean practices with organizational capacity building.

Digital technologies, particularly Building Information Modeling (BIM), enhance lean construction by supporting waste elimination, continuous improvement, and standardization through 3D visualization, rapid document generation, and model integrity maintenance [64–66]. BIM enables zero-waste strategies, circular design, prefabrication, and real-time optimization, though challenges such as limited technical expertise, weak policy guidance, and financial constraints persist [67,68].

Sustainability and zero-waste practices are central to modern construction, emphasizing alternative materials, recycling, circular economy adoption, and social sustainability. Barriers include cultural resistance, limited knowledge, and financial constraints [69,70]. Lean practices inherently support sustainability through efficiency gains and reduced material use [58,68].

SLSS adoption faces challenges, including organizational silos, weak leadership, departmental boundaries, cultural resistance, insufficient training, and technical complexity [71–75]. Service industries struggle with measuring intangible outputs and sustainability, while emerging economies often lack resources for training and technology. Critical enablers include eco-design, advanced quality tools, green procurement, and defect reduction [76–78]. Struc-

tured leadership, capacity building, continuous training, and change management, combined with MCDM techniques (AHP, DEA, ANP, TOPSIS, COPRAS, SWARA, ISM), facilitate evaluation, prioritization, and resource optimization for successful SLSS implementation [79,80].

In summary, LSS provides a robust framework for operational efficiency, process quality, and organizational learning, while SLSS extends these benefits to environmental, social, and economic dimensions. Adoption requires strategic alignment, leadership, engagement, collaboration, and systematic use of structured, data-driven tools. Leveraging these methodologies enables organizations to achieve operational excellence, sustainability, resilience, and competitive advantage across sectors.

2.2. Industry 4.0 Technologies in Project Management

Project management is critical across construction, IT, healthcare, and manufacturing [81,82]. Despite global investments exceeding \$48 trillion annually, only about 35% of projects achieve objectives, reflecting inefficiencies, resource waste, and lost value. Traditional PM tools—spreadsheets, slides, and basic tracking software—are insufficient for managing uncertainty, interdependencies, and dynamic requirements, often causing cost overruns, delays, quality issues, and operational risks.

Industry 4.0 (I 4.0) technologies enable intelligent, integrated, and data-driven workflows. Key technologies include IoT, AI, ML, digital twins (DTs), BIM, cloud computing, RPA, AR/VR, and blockchain. These facilitate predictive analytics, scenario simulation, workflow automation, and collaborative decision-making [83,84]. Real-time visibility and automation shift PM from reactive, schedule-driven approaches to proactive, resilience-oriented strategies, improving efficiency, accuracy, risk mitigation, and evidence-based decisions.

In construction, project complexity—including long timelines, interdependent tasks, and high uncertainty—renders traditional PM insufficient [85, 86]. Construction 4.0 (C 4.0) leverages I 4.0 tools such as BIM, IoT, AI, robotics, AR/VR, drones, cloud platforms, blockchain, and DTs to enable real-time monitoring, predictive planning, automated workflows, and seamless collaboration. End-to-end digital integration across planning, design, construction, operation, and maintenance improves efficiency, quality, safety, and sustainability while supporting predictive risk management and continuous improvement [87–91]. Sustainability is achieved through green building standards, life cycle assessment, energy-efficient design, sustainable sourcing, and circular construction practices [92–95].

Digital twins (DTs) create high-fidelity virtual replicas of physical assets synchronized with real-time data, enabling predictive maintenance, energy optimization, resource efficiency, and lifecycle management [96–99]. Integrated with BIM, DTs support scenario simulations, material optimization, and energy reduction [100]. At urban scales, DTs facilitate smart city planning, integrating infrastructure, mobility, and utilities for data-driven governance [101]. Real-time monitoring of water and energy consumption reduces inefficiencies, environmental impact, and extends asset lifespans [102–104].

Artificial intelligence (AI) enhances predictive planning, risk assessment, and decision-making. AI analyzes historical and real-time data, detects patterns, forecasts outcomes, and provides actionable recommendations. Applications include predictive scheduling, cost estimation, automated code generation, intelligent bug detection, resource optimization, and proactive risk mitigation [105–107]. AI improves uncertainty management and resource allocation, and reduces human bias [108–110], generating economic and social value, and is endorsed by PMI [111–113].

Over 100 AI tools are applied in PM, including Fuzzy Logic, CBR, Network Analysis, DSS, ML, Simulation, SVM, and FMEA. Fuzzy Logic, Network Analysis, and DSS are widely used for risk assessment, dependency mapping, and complex decision-making. Hybrid approaches integrating Fuzzy Logic with ML or DSS with predictive analytics, simulation, and NLP improve uncertainty management and real-time decision support. Integration with DTs strengthens predictive monitoring, scenario analysis, and operational reliability.

Despite their potential, adoption faces technological, organizational, and stakeholder challenges. Technological barriers include system integration, interoperability, cybersecurity, and data quality [114,115]. Organizational challenges include workforce skill gaps, resistance to change, and unclear processes, while stakeholder challenges include low awareness, fragmented collaboration, and unrealistic expectations [116]. Regional adoption varies: Saudi Arabia faces high costs and ambiguous objectives [117]; Malaysia benefits from technological and economic readiness [118]; India faces high initial investment and organizational resistance [119,120]. Insufficient digital skills exacerbate delays, cost overruns, and suboptimal outcomes [121].

In conclusion, I 4.0 and C 4.0 technologies—including AI, BIM, DTs, IoT, and automation—enable intelligent, lifecycle-oriented, and sustainable project management. They enhance risk management, resource optimization, collaboration, and decision-making while supporting environmental and social sustainability. Realizing their potential requires holistic integration of technology, workforce capability, process alignment, and stakeholder engagement, while addressing adoption barriers. Future research should focus on systematic frameworks that integrate AI, DTs, and LSS, evaluate effectiveness across industries, and generate empirical evidence for best practices in large-scale projects.

3. Challenges and Research Gaps Analysis

The integration of Lean Six Sigma (LSS), Sustainable Lean Six Sigma (SLSS), and Industry 4.0 (I 4.0)-enabled Project Management 4.0 (PM 4.0) offers substantial opportunities to enhance efficiency, quality, sustainability, and data-driven decision-making. However, adoption is constrained by organizational, cultural, technical, financial, and sustainability-related challenges. In addition, gaps in empirical evidence, methodological guidance, and practical frameworks limit systematic deployment across diverse project contexts.

This section analyzes key implementation challenges and identifies research gaps, supported by **Table 4**, providing insights for future research and practical strategies to achieve resilient, high-performing, and sustainable project management.

Table 4. Synthesis of Key Challenges, Research Gaps, and PM 4.0 Implications.

#	Dimension	Key Challenges	Research Gaps	PM 4.0 Implications
1	Organizational & Cultural	Resistance, silos, weak improvement culture, low digital awareness	Limited understanding of cultural change	Apply structured change management and culture-driven strategies
2	Leadership & Governance	Weak leadership, poor alignment, unclear digital vision	Limited evidence on leadership impact	Develop integrated governance models
3	Technical & Data	Poor data quality, limited analytics, silos, interoperability, cybersecurity	Lack of unified, secure data architectures	Build interoperable, standardized data ecosystems
4	Resources & Finance	Limited investment, high costs, uncertain ROI	Limited cost-effectiveness and scalability studies	Develop scalable, cost-efficient adoption strategies
5	Project Complexity	Standard tools hard to apply, multi-technology integration	Limited adaptation to complex projects	Implement flexible, hybrid project management approaches
6	Sustainability	Weak ESG alignment, low sustainability adoption	Lack of integrated process-sustainability models	Embed sustainability metrics and lifecycle tools
7	Knowledge & Learning	Poor knowledge capture/sharing, limited intelligent systems	Limited research on digital knowledge integration	Integrate AI-enabled knowledge management systems
8	Workforce & Skills	Limited process improvement and digital skills	Lack of hybrid competency models	Implement integrated workforce development programs
9	Methodological Integration	Limited LSS adaptation, weak PM integration	Lack of unified LSS-I 4.0-PM frameworks	Develop holistic, adaptable PM 4.0 frameworks
10	Empirical Validation	Few project-based studies, limited PM 4.0 validation	Lack of longitudinal evidence	Establish performance evaluation and benchmarking models
11	Standardization & Interoperability	Low standardization, poor tool interoperability	Lack of standardized frameworks	Develop standardized architectures and tools
12	Ethics & Governance	Limited data ethics, cybersecurity/governance risks	Lack of ethical governance models	Integrate secure, transparent, ethical practices

3.1. Challenges in Lean Six Sigma Implementation

Despite its demonstrated benefits, LSS implementation in project management faces multiple obstacles:

- 1) Resistance to change—Employees’ attachment to existing practices, fear of accountability, and uncertainty about new processes can limit adoption. Structured change management, stakeholder engagement, and training are essential [37,74].
- 2) Leadership and strategic alignment—Strong management support ensures prioritization, resource allocation, and effective communication, while weak leadership undermines continuous improvement [46].
- 3) Cultural and behavioral barriers—Hierarchies, silos, and limited cross-functional collaboration impede knowledge sharing and process integration [40].
- 4) Resource and technical limitations—LSS requires investment in training, monitoring tools, and analytics. Limited budgets or technical expertise can restrict effectiveness [42,71].
- 5) Project complexity and variability—Multi-stakeholder, dynamic projects challenge standardization of DMAIC, value stream mapping, and JIT methods [57,62].

- 6) Sustainability integration—SLSS requires aligning environmental, social, and economic goals with operational improvements, demanding advanced metrics and cross-functional coordination [72,75,122].
- 7) Communication and knowledge management—Ineffective knowledge sharing limits lessons learned and continuous improvement [32,40].
- 8) Sustaining improvements—Initiatives can lose momentum due to shifting priorities or staff turnover, necessitating ongoing monitoring and retraining.

In summary, effective LSS adoption requires leadership, strategic alignment, cross-functional collaboration, adequate resources, structured training, and proactive change management.

3.2. Challenges in Industry 4.0 Adoption

I 4.0 technologies—including IoT, AI, ML, digital twins, BIM, RPA, and cloud computing—enable predictive analytics, real-time monitoring, and data-driven decision-making [83,84]. Key adoption challenges include:

- 1) Technological complexity and integration—Legacy systems, interoperability issues, data silos, cybersecurity risks, and system reliability impede adoption [98,99,116].
- 2) Organizational barriers—Workforce skill gaps, resistance to change, and limited leadership support hinder implementation [117,121].
- 3) Financial constraints—High acquisition and maintenance costs affect SMEs and emerging markets [119,120].
- 4) Stakeholder-related challenges—Low awareness, misaligned objectives, fragmented communication, and socio-political factors delay adoption [118,119].
- 5) Methodological and strategic gaps—Few frameworks integrate I 4.0 tools with traditional PM methodologies, limiting scenario modeling and real-time decision-making [123].

In conclusion, successful adoption requires holistic strategies integrating technology, workforce capability, change management, stakeholder engagement, and established PM practices.

3.3. Research Gaps in Lean Six Sigma Implementation

Despite demonstrated effectiveness, several research gaps persist in LSS:

- 1) Limited empirical evidence—Underexplored in construction, engineering, and IT projects [57,62].
- 2) Sustainability integration—Limited studies on SLSS, cross-functional coordination, and real-time sustainability measurement [72,75,122].
- 3) Cultural and behavioral strategies—Few studies explore resistance mitigation, engagement, and knowledge sharing [40].
- 4) Leadership and governance—Sparse evidence linking leadership, governance, and strategic alignment to project-level outcomes.
- 5) Resource and technical readiness—Empirical examination of constraints on data, tools, and technical capacity is limited [42,71].
- 6) Knowledge management—Mechanisms for capturing lessons learned and embedding continuous improvement remain underdeveloped [32,40].
- 7) Standardization versus contextual adaptation—Limited research on adapting DMAIC or value stream mapping to complex, variable, or non-repetitive projects.

In summary, addressing these gaps supports robust, adaptable, and sustainable LSS frameworks.

3.4. Research Gaps in Project Management 4.0

PM 4.0 leverages I 4.0 technologies for predictive, data-driven, and resilient project management, yet critical gaps remain:

- 1) Integration with traditional PM methodologies—Few studies integrate AI, DTs, BIM, IoT, and RPA with LSS, Agile, or PRINCE2 [83].
- 2) Empirical validation—Limited real-world evidence on cost, schedule, quality, and safety outcomes [118,119].
- 3) Workforce readiness—Few studies address skill development, digital literacy, and human-centric adoption [121,124].

- 4) Contextual and regional disparities—SMEs, emerging economies, and resource-constrained projects remain underexplored [117,121].
- 5) Sustainability integration—Limited research on economic, environmental, and social outcomes in PM 4.0 adoption [89,93].
- 6) Cybersecurity, data governance, and ethics—Secure, ethical, and transparent frameworks are underdeveloped [114,116].
- 7) Standardization and interoperability—Lack of standardized processes and interoperability among PM 4.0 tools limits adoption consistency [98,99].

In conclusion, closing these gaps requires multidisciplinary approaches integrating technology, management, human factors, sustainability, and governance.

3.5. Synthesis of Challenges and Research Gaps for PM 4.0

Table 4 summarizes the key challenges, research gaps, and PM 4.0 implications. Successful adoption requires coordinated action across leadership, workforce, methodology, technology, and sustainability domains.

1. Organizational & Cultural—Resistance to change, silos, and low digital awareness; foster a collaborative, adaptable, and digitally competent culture.
2. Leadership & Governance—Weak leadership and misalignment; implement clear governance structures, strategic alignment, and a strong digital vision.
3. Technical & Data—Fragmented systems, poor data quality, and cybersecurity risks; establish secure, interoperable, and standardized data infrastructures.
4. Resources & Finance—Limited budgets and high costs; adopt scalable, cost-effective strategies with transparent ROI tracking.
5. Project Complexity—Standard tools struggle with multi-stakeholder, multi-technology projects; apply flexible, hybrid project management approaches.
6. Sustainability—Weak ESG integration; embed environmental, social, and economic metrics into project processes.
7. Knowledge & Learning—Ineffective knowledge capture and sharing; leverage AI-enabled systems to institutionalize lessons learned and support continuous improvement.
8. Workforce & Skills—Gaps in digital literacy and process improvement capabilities; implement comprehensive upskilling and hybrid competency programs.
9. Methodological Integration—LSS, PM methods, and I 4.0 tools are poorly integrated; develop holistic and adaptable PM 4.0 frameworks.
10. Empirical Validation—Limited real-world evidence on PM 4.0 outcomes; establish benchmarking, monitoring, and performance evaluation mechanisms.
11. Standardization & Interoperability—Low process standardization and poor tool integration; create standardized, interoperable frameworks for consistent adoption.
12. Ethics & Governance—Limited focus on data ethics and cybersecurity; ensure secure, transparent, and ethically robust project management practices.

Adopting PM 4.0 successfully requires a holistic, coordinated approach across organizational culture, leadership, technology, resources, project complexity, sustainability, knowledge, workforce, methodology, empirical validation, standardization, and ethics to achieve resilient, data-driven, and sustainable project outcomes.

In conclusion, systematically addressing these interconnected challenges and bridging the identified research gaps is essential to operationalizing PM 4.0 principles effectively. Integrating leadership, workforce development, methodology, technology, sustainability, and governance enables organizations to enhance efficiency, decision-making, and long-term project performance, establishing a foundation for future-ready, high-performing, and sustainable project management.

4. A Conceptual Mapping for Project Management 4.0

Modern projects face increasing complexity, rapid technological advancements, and evolving stakeholder expectations. Traditional linear project management approaches often struggle to manage interdependencies, ac-

celerated timelines, and high-performance requirements. Project Management 4.0 (PM 4.0) addresses these challenges by integrating Lean Six Sigma (LSS) methodologies with Industry 4.0 technologies, combining structured process rigor with real-time digital intelligence. This integration enables adaptive, data-driven, and value-focused project management systems, capable of predictive decision-making, enhanced collaboration, and continuous improvement.

This section presents the methodology for PM 4.0 in two parts. Section 4.1 maps project management functions to LSS tools and Industry 4.0 technologies, establishing a conceptual framework. Section 4.2 illustrates the integration of the DMAIC framework into PM 4.0, demonstrating how structured LSS methods and digital technologies together enable resilient, high-performing project management.

4.1. Mapping Project Management Functions to LSS and Industry 4.0 Technologies

Modern projects require integrated, adaptive, and data-driven management approaches. LSS enhances process efficiency, quality, and predictability, while Industry 4.0 technologies—AI, IoT, digital twins, RPA, and cloud platforms—enable real-time monitoring, predictive insights, automation, and collaboration.

Table 5 shows how LSS tools and Industry 4.0 technologies form a synergistic ecosystem. **Figure 3** visualizes this framework, positioning LSS at the core to drive process excellence, with Industry 4.0 technologies as enablers across the lifecycle. The six primary functions include:

- 1) **Strategic Governance & Alignment:** LSS tools (VOC analysis, SIPOC diagrams, KPI dashboards) structure requirement definition and performance tracking. AI analytics, blockchain, and cloud platforms improve transparency, accountability, and predictive resource allocation.
- 2) **Planning & System Design:** LSS methods (process mapping, FMEA, value stream mapping) identify inefficiencies and anticipate risks. Digital twins, simulations, and IoT sensors support scenario testing, real-time monitoring, and proactive resource planning.
- 3) **Execution & Coordination:** LSS tools (DMAIC, Standard Work, 5S, Kanban) standardize workflows and reduce errors. IoT, RPA, AR/VR, and cloud collaboration platforms enable real-time tracking and cross-functional coordination.
- 4) **Monitoring, Control & Adaptation:** LSS tools (SPC, control charts, root cause analysis) ensure quality and oversight. AI/ML, IoT sensors, and dashboards enable early risk detection and adaptive decision-making.
- 5) **Learning & Continuous Improvement:** Kaizen events, PDCA cycles, and lessons-learned mechanisms capture knowledge. Digital repositories and AI-driven analytics enhance organizational learning and best-practice dissemination.
- 6) **Closure & Value Realization:** Performance audits, process capability analysis, blockchain, digital twins, and dashboards validate outcomes, enhance traceability, and support post-project evaluation.

Table 5. Integration of PM Functions, LSS Tools, and Industry 4.0 Technologies in PM 4.0.

#	PM Function	Representative LSS Tools	Industry 4.0 Technologies	Applications/Impact
1	Strategic Governance & Alignment	VOC Analysis, SIPOC, KPI Dashboards	AI Analytics, Cloud Platforms, Blockchain	Aligns projects with organizational strategy; ensures transparency, accountability, and predictive resource allocation; enables data-driven strategic decision-making
2	Planning & System Design	Process Mapping, FMEA, Value Stream Mapping	Digital Twins, Simulation Models, IoT Sensors	Optimizes project workflows; anticipates risks; enables scenario-based planning, resource optimization, and proactive scheduling
3	Execution & Coordination	DMAIC, Standard Work, 5S, Kanban	IoT, RPA, AR/VR, Cloud Collaboration Platforms	Improves operational efficiency; reduces errors and rework; enhances team coordination, real-time communication, and task tracking
4	Monitoring, Control & Adaptation	SPC, Control Charts, Root Cause Analysis	AI/ML Predictive Analytics, IoT Sensors, Real-Time Dashboards	Enables continuous monitoring; supports predictive risk management; improves quality control, process stability, and adaptive decision-making
5	Learning & Continuous Improvement	Kaizen Events, PDCA, Lessons Learned Capture	Digital Knowledge Repositories, AI Insights, Analytics	Fosters organizational learning; drives iterative process improvement; captures knowledge for future projects; strengthens innovation capability
6	Closure & Value Realization	Performance Audits, Process Capability Analysis	Blockchain, Digital Twins, Reporting Dashboards	Validates project deliverables and alignment with objectives; measures ROI and value creation; ensures stakeholder satisfaction and knowledge retention

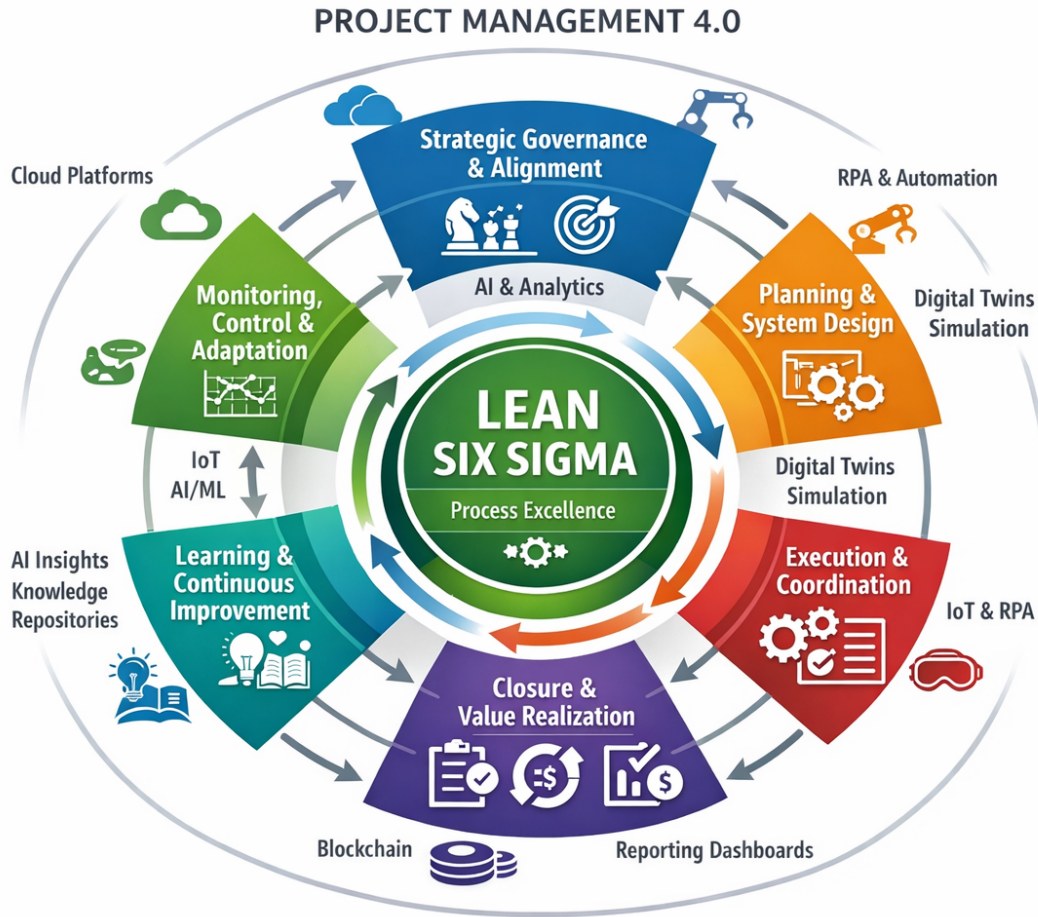


Figure 3. Project Management PM 4.0 framework.

Mapping PM functions to LSS tools and Industry 4.0 technologies bridges methodological rigor with digital intelligence, creating adaptive, resilient, and performance-oriented project management systems.

4.2. Integration of Lean Six Sigma DMAIC Framework into PM 4.0

The DMAIC framework—Define, Measure, Analyze, Improve, Control—is central to LSS, providing a structured, data-driven methodology for process optimization, quality assurance, and risk management. Integrating DMAIC into PM 4.0 combines methodological discipline with digital intelligence, enabling efficient, adaptive, and value-focused project execution.

Table 6 maps DMAIC phases to PM 4.0 functions, linking LSS tools with Industry 4.0 technologies. Figure 4 visualizes this integration in a circular, iterative layout, emphasizing continuous improvement and adaptive learning.

Table 6. Integration of DMAIC Framework into PM 4.0.

#	Phase	PM 4.0 Function	Representative LSS Tools	Industry 4.0 Technologies	Applications/Impact
1	Define	Strategic Governance & Alignment	VOC Analysis, SIPOC, KPI Dashboards, Project Charter	AI Analytics, Cloud Platforms, Collaboration Tools	Define project objectives, align stakeholders, establish success criteria, enable predictive resource planning, and ensure strategic value delivery
2	Measure	Planning & System Design	Process Mapping, Check Sheets, Baseline Metrics	IoT Sensors, Digital Twins, Dashboards	Quantify performance, establish baselines, monitor resources in real time, optimize schedules, and enhance data-driven planning and transparency

Table 6. Cont.

#	Phase	PM 4.0 Function	Representative LSS Tools	Industry 4.0 Technologies	Applications/Impact
3	Analyze	Monitoring, Control & Adaptation	FMEA, Pareto Analysis, SPC	AI/ML, Predictive Analytics	Identify root causes of inefficiencies and risks, forecast potential failures, prioritize improvements, and enable proactive, evidence-based decision-making
4	Improve	Execution & Coordination	Kaizen Events, Standard Work, Process Redesign	RPA, Automation, AR/VR Simulations, Digital Twins	Optimize workflows, reduce waste and errors, improve quality, enable rapid testing and adaptive deployment, and strengthen collaboration
5	Control	Learning & Continuous Improvement/Closure & Value Realization	Control Charts, Audits, Performance Reviews	Real-time Dashboards, Predictive Alerts, IoT Monitoring, AI Governance Tools	Sustain performance, maintain process stability, institutionalize lessons learned, foster continuous improvement, and enhance resilience, accountability, and compliance

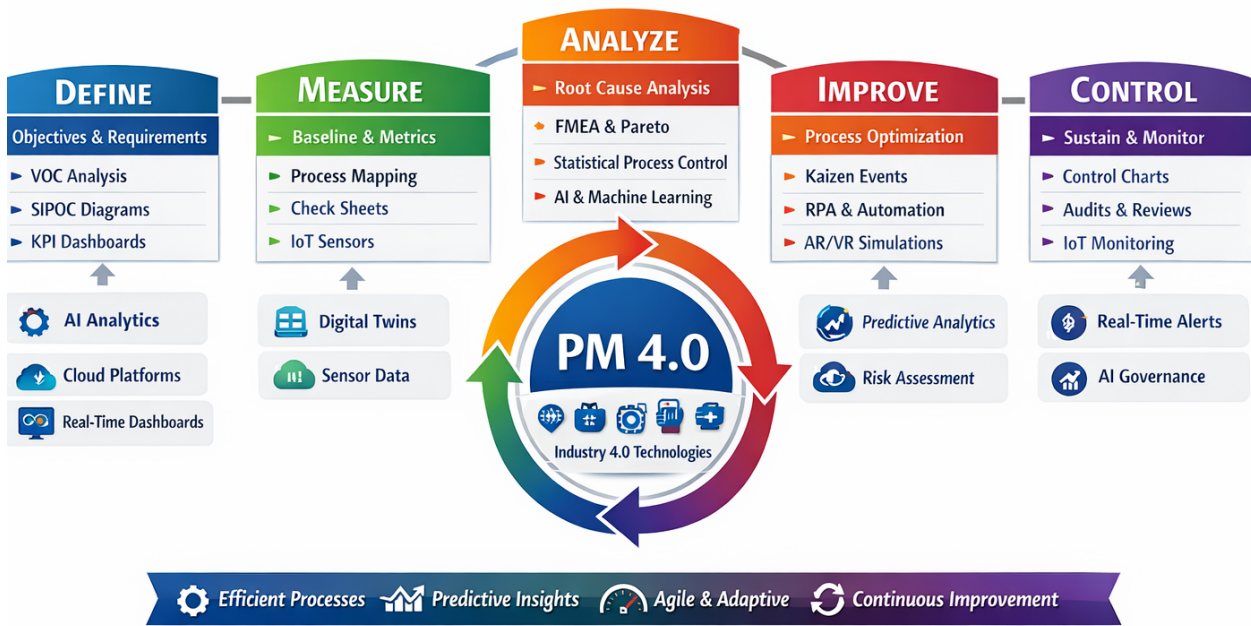


Figure 4. Integration of LSS DMAIC Framework with PM 4.0.

- 1) Define: Establish objectives, stakeholder requirements, and strategic alignment. LSS tools (VOC analysis, SIPOC diagrams, KPI dashboards) define success metrics, while AI analytics, cloud dashboards, and collaborative platforms provide real-time visibility into priorities, resources, and interdependencies.
- 2) Measure: Quantify processes and establish baselines. LSS tools (process mapping, check sheets) combined with IoT sensors, digital twins, and interactive dashboards enable continuous monitoring of cost, schedule, quality, and resource utilization.
- 3) Analyze: Identify root causes of inefficiencies, risks, and variability. LSS techniques (FMEA, Pareto analysis, SPC) with AI/ML detect patterns, forecast potential failures, and prioritize improvement opportunities, transforming reactive problem-solving into predictive risk management.
- 4) Improve: Implement solutions to optimize workflows, reduce waste, and enhance quality. LSS practices (Kaizen events, process standardization, workflow redesign) integrate with RPA, AR/VR, automation, digital twins, and collaboration platforms, enabling rapid testing, validation, and deployment aligned with strategic objectives.
- 5) Control: Ensure sustained performance, stability, and continuous improvement. LSS tools (control charts, audits, review cycles) reinforced by dashboards, predictive alerts, IoT monitoring, and AI governance systems enable early deviation detection and adaptive corrective actions, institutionalizing improvements for future projects.

Integration & Impact: Embedding DMAIC into PM 4.0 establishes a comprehensive, adaptive, and intelligent project management ecosystem, enabling organizations to:

- 1) Optimize processes and reduce variability;
- 2) Enhance data-driven decision-making;
- 3) Increase agility and resilience;
- 4) Maximize stakeholder value through strategic alignment;
- 5) Foster continuous improvement and organizational learning.

In conclusion, integrating DMAIC into PM 4.0 is a transformational approach to modern project management. By merging LSS structured methodologies with Industry 4.0 digital intelligence, organizations achieve adaptive, intelligent, and value-driven practices, delivering operational excellence, superior project outcomes, and sustained competitive advantage.

5. Conclusions

This study introduces Project Management 4.0 (PM 4.0), an integrative framework that combines Lean Six Sigma (LSS) methodologies with Industry 4.0 technologies to address the growing complexity, uncertainty, and digital transformation of modern projects. By systematically linking core project management functions—Strategic Governance & Alignment, Planning & System Design, Execution & Coordination, Monitoring, Control & Adaptation, Learning & Continuous Improvement, and Closure & Value Realization—to LSS tools and aligning them with technologies such as AI, IoT, digital twins, RPA, AR/VR, and cloud platforms, PM 4.0 provides a structured, adaptive, and data-driven approach to project management.

The integration of the DMAIC framework strengthens PM 4.0 by embedding iterative processes for problem-solving, predictive risk management, process optimization, and continuous improvement. By combining methodological rigor with digital intelligence, the framework enhances planning, execution, monitoring, and control, enabling projects to be efficient, agile, resilient, and strategically aligned. PM 4.0 emphasizes continuous learning, real-time feedback, and performance transparency, demonstrating how digital technologies support intelligent decision-making, higher quality, and enhanced stakeholder value throughout the project lifecycle.

Beyond theoretical contributions, PM 4.0 offers practical guidance for managers, practitioners, and researchers, providing a roadmap for implementing intelligent, high-performing, and value-focused project management systems. It highlights the integration of human expertise with digital capabilities, fosters collaboration, and institutionalizes knowledge for sustained improvement.

- **Theoretical Contributions:** PM 4.0 advances project management theory by integrating traditional methodologies with digital intelligence, emphasizing adaptability, resilience, and continuous improvement.
- **Practical Implications:** Organizations can leverage PM 4.0 to optimize processes, enable data-driven decision-making, and achieve consistent value delivery in complex projects.
- **Managerial Implications:** The framework guides managers in using LSS tools alongside Industry 4.0 technologies to improve planning, execution, monitoring, and control, while promoting collaboration, knowledge sharing, and stakeholder satisfaction.
- **Study Limitations:** Empirical validation across industries and project types is needed to fully assess PM 4.0's effectiveness, scalability, and adaptability.
- **Future Research Directions:** Future studies should refine and test PM 4.0 through case studies, surveys, experiments, and longitudinal research. Key avenues include:
 - 1) Empirical validation: Evaluating PM 4.0's effectiveness, adaptability, and scalability.
 - 2) Human-centric digital integration: Aligning Industry 4.0 technologies with culture, leadership, and team dynamics.
 - 3) Intelligent governance and decision support: Leveraging AI-driven predictive tools and automated risk assessment.
 - 4) Sustainability and resilience assessment: Assessing PM 4.0's impact on environmentally responsible, socially aware, and adaptive project management.

Integration with emerging paradigms: Exploring Industry 5.0 and 6.0 to advance human-centric, ethical, and

regenerative project management approaches.

By pursuing these directions, PM 4.0 can evolve into a robust, intelligent, and high-performing framework, capable of transforming modern project management and delivering sustainable value in increasingly complex, digitally enabled environments.

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Abbreviations

Abbreviation	Full Term	Short Definition
3D Printing	Additive Manufacturing	Layered object creation.
5S	Sort, Set in order, Shine, Standardize, Sustain	Workplace organization method.
AHP	Analytic Hierarchy Process	Structured decision analysis.
AI	Artificial Intelligence	Systems performing human-like tasks.
APIs	Application Programming Interfaces	Software communication protocols.
AR	Augmented Reality	Digital overlay on reality.
BC	Blockchain	Secure, transparent ledger.
CE	Circular Economy	Reuse and sustainability model.
CPS	Cyber-Physical Systems	Integrated physical and digital systems.
DMAIC	Define, Measure, Analyze, Improve, Control	Lean Six Sigma framework.
DSS	Decision Support System	System aiding decision-making.
DT	Digital Twin	Digital replica of assets.
EAI	Ethical AI	AI follows ethical standards.
FL	Fuzzy Logic	Reasoning with uncertainty.
FMEA	Failure Mode and Effects Analysis	Identifying potential failures.
HDT	Human Digital Twin	Digital model of humans.
IoT	Internet of Things	Network of smart devices.
IT	Information Technology	Managing and processing information.
JIT	Just-In-Time	Materials delivered as needed.
KPI	Key Performance Indicator	A metric to measure performance.
LSS	Lean Six Sigma	Efficiency and quality method.
ML	Machine Learning	AI learning from data.
PM	Project Manager	Leads project execution.

PMBOK	Project Management Body of Knowledge	Standard project guide.
PMI	Project Management Institute	Project management organization.
SMEs	Small and Medium-sized Enterprises	Small to medium businesses.
SPC	Statistical Process Control	Statistical process monitoring.
VSM	Value Stream Mapping	Visualizing workflow.
VR	Virtual Reality	Immersive digital environment.

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