

# Redesigning Lean for Sustainability: A Risk-Aware VSM Framework for Continuous Improvement in Manufacturing

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## ABSTRACT

*Manufacturing systems face the dual imperative of achieving operational excellence while meeting stringent sustainability and resilience goals. Traditional Lean and Value Stream Mapping (VSM) approaches, however, often lack structured risk management and fail to account for the impact of process variability on holistic sustainability performance. This study proposes and validates a novel Sustainability–Risk–Variability Value Stream Mapping (Sus-Risk-VVSM) framework, designed to bridge this gap. The framework systematically integrates the ISO 31000 risk management cycle and Triple Bottom Line (TBL) metrics into the Lean Six Sigma DMAIC structure. Validation involved a two-round Delphi study with industry and academic experts, confirming the clarity and relevance of the findings. A Monte Carlo simulation of a discrete manufacturing process demonstrated the framework's superior performance, reducing process variability by 26%, lowering operational risk exposure by 35%, and improving a composite Sustainability Index by 30.2% compared to conventional VSM. Statistical analysis identified process variability ( $r = -0.71$ ) and defect rate ( $r = -0.73$ ) as the strongest predictors of sustainability outcomes. The study contributes a validated, integrated model that transforms Lean into a proactive, risk-aware tool for sustainable decision-making, supporting the transition to resilient, sustainable Industry 4.0 operations.*

**Keywords:** Lean Sustainability, Monte Carlo Simulation, Risk-Aware VSM, Sustainable Manufacturing, Sus-Risk-VVSM.

## 1. INTRODUCTION

Over the past decade, manufacturing systems have evolved from stability-driven optimization toward transformation centered on resilience, adaptability, and sustainability. Foundational literature identifies Lean as a cornerstone of modern manufacturing transformation, providing a baseline for efficiency-driven improvement and guiding research evolution across diverse industrial contexts [1]. The acceleration of global disruptions such as the COVID-19 pandemic, semiconductor shortages, logistics congestion, and escalating ESG (Environmental, Social, and Governance) compliance has exposed structural weaknesses in traditional Lean systems that were designed primarily for predictable, efficiency-focused environments [2], [3], [4], [5], [6]. These disruptions revealed that efficiency alone is insufficient to ensure organizational resilience, as supply chain volatilities, resource scarcity, and social responsibility pressures increasingly shape the competitiveness of manufacturing enterprises.

While Lean Manufacturing remains a foundational philosophy for eliminating waste and enhancing process flow, its deterministic and static nature limits applicability in Volatile,

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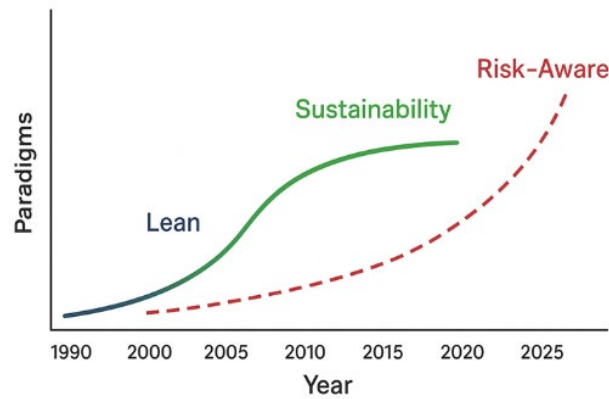
Uncertain, Complex, and Ambiguous (VUCA) environments [2], [7], [8], [9]. The integration of Lean and Six Sigma, commonly referred to as Lean Six Sigma (LSS), has enhanced process capability through data-driven problem-solving. Yet, it traditionally emphasizes operational stability and defect reduction rather than sustainability outcomes. Recent studies highlight that Lean implementation can promote sustainability through resource conservation, workforce engagement, and innovation in process improvement [10], [11], [12], [13], [14], [15]. This relationship has been reinforced by recent systematic reviews demonstrating that Green Lean Six Sigma (GLSS) provides a structured approach for sustainability-driven performance improvement [16]. However, contemporary manufacturing is influenced by interconnected challenges, such as carbon-neutrality mandates, digital transformation, and resilience to systemic shocks that extend beyond the original Lean and LSS paradigms [2], [17], [18]. This industrial transition has also increased demand for new competencies and educational programs specializing in Lean and digital manufacturing technologies [19].

Emerging concepts such as Digital Lean and Sustainability 4.0 have sought to address these gaps by aligning Lean practices with ESG goals and circular-economy principles [20], [21], [22], [23]. Recent advances indicate that simulation-enabled Value Stream Mapping (VSM) can enhance decision-making accuracy in digital Lean environments, particularly when integrated with discrete-event simulation frameworks [24]. Nevertheless, these approaches often lack explicit integration of structured risk management. Additionally, recent literature highlights that the convergence of lean, green, and resilient supply chain practices can strengthen sustainable performance measurement, reinforcing the importance of sustainability-driven operational transformation [25]. While Sustainable Value Stream Mapping (Sus-VSM) extends the traditional VSM by incorporating environmental performance indicators such as carbon emissions and energy use [26], [27]. It rarely accounts for risk awareness and social sustainability dimensions [6], [18], [28], [29], [30].

To address these limitations, this study proposes the Sustainability–Risk–Variability Value Stream Mapping (Sus-Risk-VVSM) framework, which reconceptualizes Lean thinking by integrating sustainability principles, risk management, and process variability. This framework systematically embeds the ISO 31000:2018 risk management cycle within the DMAIC (Define, Measure, Analyze, Improve, and Control) structure and aligns it with the Triple Bottom Line sustainability paradigm encompassing economic, environmental, and social dimensions. Through this integrative design, Sus-Risk-VVSM aims to strengthen Lean's adaptability, resilience, and sustainability performance in an increasingly dynamic and uncertain global manufacturing environment [15], [31], [32], [33].

Figure 1 illustrates the evolutionary trajectory of three major paradigms in operations and manufacturing management: Lean, Sustainability, and Risk-Aware from 1990 to 2025. The Lean paradigm shows a steady rise beginning in the early 1990s, with stabilization around 2010. Sustainability has experienced substantial growth since 2005, reflecting the growing global emphasis on the economic, environmental, and social dimensions of production systems. The Risk-Aware paradigm, depicted by the red dashed line, demonstrates a sharp projected increase after 2020, indicating the growing industrial need for operational approaches that are resilient to uncertainty, disruptions, and process variability.

The integration of sustainability within Lean systems has progressively advanced through the evolution of Sus-VSM, which expands traditional VSM by incorporating environmental indicators such as energy consumption, carbon footprint, and waste intensity [26], [27]. This integration enables organizations to visualize ecological performance along with process efficiency, demonstrating the potential alignment between Lean and sustainability objectives. However, despite this advancement, Sus-VSM largely concentrates on environmental aspects, with minimal consideration of social sustainability dimensions such as occupational health, ergonomic safety, and worker well-being [12], [34].



**Figure 1:** Evolution of Lean, Sustainability, and Risk-Aware Paradigms Over Time

Moreover, existing Lean-based models are predominantly deterministic, assuming steady-state process conditions and predictable demand. In contrast, modern manufacturing systems operate under uncertainty driven by market volatility, supply variability, and disruption risks [7], [35]. Consequently, traditional VSM lacks the capacity to represent how process variability influences both operational and sustainability outcomes, limiting its diagnostic and predictive capability in dynamic contexts.

Lean Six Sigma partially addresses process variation through statistical methods, yet it does not explicitly integrate structured risk governance frameworks such as ISO 31000. This absence leads to improvement initiatives that may neglect systemic risk factors affecting long-term stability and sustainability [33], [36]. Without embedding risk identification, assessment, and mitigation within Lean improvement cycles, the resulting strategies remain reactive and efficiency-centered rather than resilience-oriented.

From a theoretical standpoint, integrating risk management (ISO 31000) and Triple Bottom Line (TBL) sustainability metrics into the DMAIC structure provides a coherent approach to bridge these gaps. ISO 31000 ensures systematic risk identification and mitigation across all DMAIC phases, while TBL provides multidimensional sustainability evaluation encompassing economic, environmental, and social dimensions. The synergy of these frameworks provides a foundation for a risk-aware Lean paradigm that adapts to volatility while pursuing sustainable outcomes.

Although studies such as Araibi, Shaiful, and Shadhar (2023) [38] have initiated the integration of VSM with risk evaluation, these efforts remain limited in scope. Meanwhile, the proposed Sus-Risk-VVSM framework addresses these deficiencies by integrating risk assessment, process variability modeling, and TBL-based sustainability indicators within the Lean DMAIC cycle. This integration transforms Lean from a deterministic improvement tool into a probabilistic, risk-informed framework for sustainable decision-making.

**Table 1:** Chronological Development of Lean and Sustainability Integration.

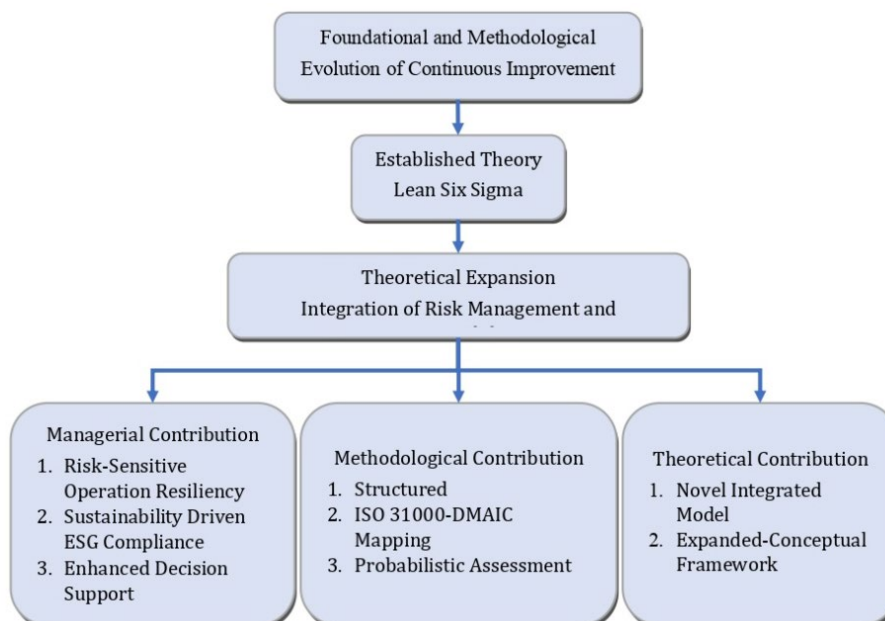
Period	Key Concept	Focus Area	Representative Studies
1990–2000	Lean Production	Waste elimination	[39], [40]
2000–2010	Lean + Green	Resource efficiency	[41], [42]
2010–2020	Sustainable Lean	Environmental & social performance	[34], [43]
2020–2025	Risk-Aware Sustainable Lean	Resilience, variability, ESG alignment	[33], [44]

This evolution underscores the growing need for a systemic framework that unites lean's process orientation with sustainability- and risk-based decision-making.

The literature review identifies three persistent research gaps that continue to challenge the field [45]. First, there is a significant lack of integration between probabilistic risk management and Lean improvement tools, which often results in frameworks that fail to account for operational uncertainties [6], [7], [46]. Furthermore, the representation of Triple Bottom Line (TBL) indicators remains incomplete, with the social dimension of sustainability being frequently overlooked in favor of environmental and economic metrics [47], [48], [49]. Finally, there is a widespread neglect of process variability as a critical risk factor influencing sustainability outcomes, thereby limiting the effectiveness of deterministic continuous improvement strategies [35], [36].

The primary objective of this research is to develop and validate the Sustainability–Risk–Variability Value Stream Mapping (Sus-Risk-VVSM) framework as an integrated solution for modern manufacturing systems. This study seeks to systematically embed ISO 31000:2018 risk management principles and Triple Bottom Line (TBL) sustainability metrics into the Lean Six Sigma DMAIC structure to establish a risk-aware foundation for continuous improvement. Furthermore, the research aims to demonstrate how process variability modeling and probabilistic simulation can enhance decision-making precision compared to traditional, deterministic Lean tools. Finally, the framework is validated through a Delphi expert assessment and Monte Carlo simulation to ensure its relevance and effectiveness in addressing current industrial dynamics.

From a theoretical perspective, this study contributes significantly by expanding the Lean Six Sigma body of knowledge by integrating risk management and sustainability as inherent operational dimensions, thereby supporting the transition toward the Lean 5.0 paradigm. Additionally, it strengthens the theoretical grounding of social sustainability, which has been frequently overlooked in the value stream mapping literature. Methodologically, the research introduces probabilistic simulation techniques to quantify risk and variability, providing a sharper diagnostic tool for identifying process vulnerabilities. Lastly, in terms of managerial implications, this study provides a structured, practical guide for industry practitioners to redesign production processes that are resilient to disruptions and aligned with international standards such as ISO 9001, 14001, 45001, and 31000.



**Figure 2:** Conceptual Structure of Theoretical, Methodological, and Managerial Contributions.

## 2. METHODOLOGY

Figure 2 illustrates the conceptual progression of the study, beginning with the foundational development of continuous improvement and the established LSS theory, followed by the proposed theoretical expansion that integrates risk management and sustainability. This progression culminates in three key contributions: managerial contributions related to operational resilience and ESG-driven sustainability, methodological contributions through the structured incorporation of ISO 31000 into the DMAIC framework, and theoretical contributions in the form of a novel integrated model and an expanded conceptual framework.

### 2.1 Conceptual Model Development

The conceptual architecture of the Sus-Risk-VVSM framework was constructed. The development process involved three core integration activities:

- i. Integration of ISO 31000 with DMAIC: The steps of the ISO 31000:2018 risk management process (Establish Context, Risk Identification, Analysis, Evaluation, Treatment, Monitoring & Review) were meticulously mapped onto the corresponding phases of the Lean Six Sigma DMAIC cycle. This ensures risk governance is an inherent, procedural part of every improvement project.
- ii. Alignment with TBL Sustainability Metrics: For each DMAIC phase, relevant economic (e.g., cost, throughput), environmental (e.g., energy use, carbon emissions), and social (e.g., safety incidents, ergonomic score) metrics were identified and integrated into the activity set. This ensures sustainability assessment is not a separate audit but a concurrent evaluation.
- iii. Incorporation of Variability Analytics: Process variability ( $\sigma$ ) was explicitly defined as a key measured variable and treated as a primary source of operational risk. The framework mandates its quantification and analysis to understand its propagation into risk exposure and sustainability performance.

### 2.2 Validation

The validation process used the Delphi method to obtain expert consensus on the conceptual framework. The method involved multiple rounds of questionnaires, where each round generated feedback that was statistically and qualitatively analyzed until consensus was achieved. The outcome was a framework validated by the expert panel's perspectives and professional judgments.

### 2.3 Simulation-Based Evaluation Using Monte Carlo Analysis

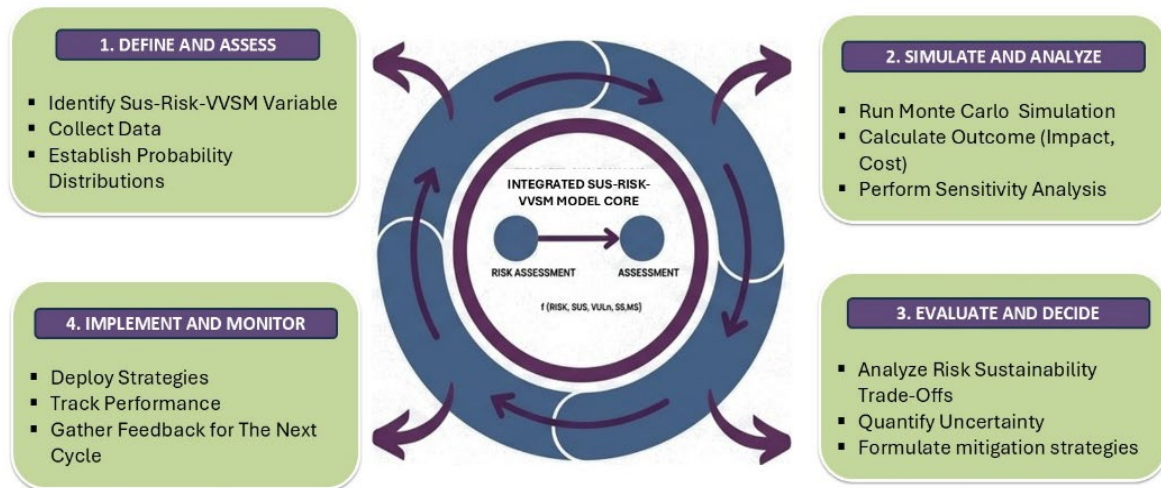
Following expert validation, a Monte Carlo simulation was employed to test the framework's analytical performance under conditions of uncertainty. A discrete-event simulation model was built to represent a typical five-stage discrete manufacturing process: material preparation, component assembly, inspection, packaging, and delivery. Key input parameters (e.g., cycle time, defect rate, energy consumption per operation) were modelled not as fixed values but as probability distributions (Normal, Triangular) based on literature data ranges, introducing realistic stochastic variability.

Three primary Key Performance Indicators (KPIs): process variability, operational risk exposure, and composite Sustainability Index (SI) were tracked. The simulation was run for 100 iterations to achieve stable statistical output. The performance was compared, and the simulation output dataset was analyzed using descriptive statistics, inferential statistics, and regression analysis.

### 3. RESULTS AND DISCUSSION

#### 3.1 Validated Sus-Risk-VVSM Framework Structure

This study successfully developed and validated the Sus-Risk-VVSM framework, as shown in Figure 3. The framework synthesizes three foundational pillars: the Lean Six Sigma DMAIC cycle, the ISO 31000:2018 risk management process, and TBL sustainability metrics. The key innovation is the procedural mapping of risk management activities onto each DMAIC phase, creating an integrated workflow for risk-aware sustainable improvement.



**Figure 3:** The Validated Sus-Risk-VVSM Framework Architecture.

The operational logic of the framework is detailed in Table 2, which specifies how each DMAIC phase is augmented with explicit risk governance and sustainability assessment tasks. For instance, during the Define phase, the ISO 31000 step of “Establishing the Context” is applied to identify not only process boundaries but also key sustainability stakeholders and risk sources. This structured integration ensures that every improvement initiative is concurrently evaluated for its impact on process stability, risk exposure, and economic, environmental, and social performance.

**Table 2:** The operational logic of the framework.

DMAIC Phase	Integrated ISO 31000 Process	Key TBL Metrics Considered	Output/Deliverable
Define	Context Establishment, Risk Identification	Stakeholder expectations, regulatory & ESG requirements	Risk-aware project charter with sustainability goals
Measure	Risk Analysis (Probability & Impact)	Baseline data: Energy use (Env), Cost (Econ), Safety incidents (Soc)	Quantified process variability ( $\sigma$ ) and initial Risk Priority Number (RPN)
Analyze	Risk Evaluation	Correlation analysis between process parameters and TBL metrics	Prioritized root causes linking variability to risk and sustainability loss
Improve	Risk Treatment	Improvement actions evaluated for TBL impact (e.g., carbon reduction, ergonomic benefit)	Implemented countermeasures with forecasted risk reduction and SI improvement
Control	Monitoring & Review	Control charts for key sustainability indicators (e.g., defect rate, energy efficiency)	Updated risk register and sustained SI performance dashboard

### 3.2 Simulation-Based Performance and Comparative Analysis

A Monte Carlo simulation ( $n=100$  iterations) of a five-stage discrete manufacturing process was conducted to compare the performance of Sus-Risk-VVSM against two benchmarks: traditional VSM and Sustainable VSM (Sus-VSM). The results are presented in Table 3.

**Table 3:** Comparative Performance Analysis of VSM, Sus-VSM, and Sus-Risk-VVSM.

Performance Indicator	Traditional VSM	Sus-Risk-VVSM (Proposed)	Improvement of Sus-Risk-VVSM vs. Traditional VSM
Process Variability ( $\sigma$ - Standard Deviation)	1.00	0.74	-26%
Operational Risk Exposure (Avg. RPN)	8.2	5.3	-35%
Composite Sustainability Index (SI)	0.63	0.82	+30.2%

The results of the Monte Carlo simulations provide quantitative evidence of the framework's performance. The effectiveness is demonstrated by significant reductions in process variability (-26%) and operational risk exposure (-35%), coupled with a substantial improvement in the composite Sustainability Index (+30.2%). The 30.2% improvement in the Sustainability Index underscores the framework's ability to translate operational stability and risk mitigation into tangible, multidimensional sustainability gains. This performance is attributed to the framework's systematic approach to identifying and addressing variability-driven risks that erode economic, environmental, and social outcomes.

These results directly address the identified research gaps. First, the structured embedding of the ISO 31000 cycle within DMAIC systematically closes the gap in risk governance within Lean tools, moving improvement initiatives from a reactive to a proactive, resilience-oriented stance. Second, the mandatory inclusion of social metrics (e.g., safety, ergonomics) alongside economic and environmental indicators within the TBL assessment rectifies the narrow, often purely environmental, focus of previous Sus-VSM approaches. Finally, by explicitly modeling process variability as a core risk factor and demonstrating its strong negative correlation with sustainability performance ( $r = -0.71$ ), this study overcomes the deterministic limitation of traditional VSM. The findings empirically substantiate that controlling variability is not merely an operational concern but a fundamental prerequisite for achieving sustainability.

### 3.3 Statistical Relationships

To decipher the mechanistic links within the framework, correlation and regression analyses were performed on the simulation-generated dataset. The results, summarized in Table 4, identify the key drivers of sustainability performance.

**Table 4:** Correlation Analysis between Process Parameters and the Sustainability Index (SI).

Process Parameter	Mean Value	Correlation with SI (Pearson's $r$ )	Strength & Direction of Relationship
Defect Rate (%)	4.7	-0.73	Strong Negative
Process Variability ( $\sigma$ )	0.58	-0.71	Strong Negative
Risk Priority Number (RPN)	167	-0.68	Moderately Strong Negative
Energy Intensity (kWh/unit)	11.2	-0.60	Moderate Negative
Lead Time (hours)	2.95	-0.64	Moderate Negative

The analysis confirms that defect rate and process variability are the strongest predictors of sustainability performance (SI), with correlation coefficients of -0.73 and -0.71, respectively. This empirical evidence validates the core premise of Sus-Risk-VVSM: controlling process variation is not merely an operational goal but a fundamental prerequisite for achieving sustainability.

#### 4. CONCLUSION

The Sus-Risk-VVSM framework was created to bridge the important gap between deterministic Lean practices and the changing needs of sustainable manufacturing. The study establishes that integrating the ISO 31000 risk management cycle and TBL metrics into the Lean Six Sigma DMAIC structure effectively transforms VSM into a proactive, risk-aware tool for holistic improvement.

The main findings, validated through a Delphi expert panel and Monte Carlo simulations, demonstrate the significant effectiveness of the framework. Compared to the traditional VSM, the Sus-Risk-VVSM shows a decrease in process variability of about 26%, an increase in operational risk of about 35%, and a rise in the composite index of about 30.2%. Statistical analysis strongly identifies process variability ( $r = -0.71$ ) and defect rate ( $r = -0.73$ ) as the strongest negative predictors of sustainability performance, empirically validating the core integration logic of the framework.

Future research should focus on three main avenues: Conducting longitudinal case studies to apply and refine the framework in real-world settings, assessing context-specific adaptations and longitudinal impact; Adding new technologies, like the Internet of Things (IoT) for real-time data feeds, artificial intelligence (AI) for risk prediction, and digital twins for dynamic simulation, to make Sus-Risk-VVSM a proactive, adaptable system that helps people make decisions; Systemic extension of the framework's scope to analyze risk and sustainability interdependencies across entire supply networks, assessing propagation effects and systemic resilience.

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