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Lean Supply Chain 4.0: An Integrative Literature Review of Digital Technologies, Supply Chain Coordination, and Operational Performance

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Abstract - With increasingly complex production systems there is an increased need for efficient, flexible, coordinated and sustainable supply chains. Lean manufacturing techniques and Lean Six Sigma (LSS) have been developed to reduce waste, variability and improve quality. Industry 4.0 techniques such as IoT, AI, Big Data, Digital Twins, Blockchain and Cyber Physical Systems provide new opportunities to monitor, predict, automate and share information using digital technologies. Despite having similar aims in improving processes, there are challenges to combine Lean techniques with Industry 4.0 techniques within supply chain networks due to differences in technology, organisational barriers, lack of skills and a lack of a framework that can be applied universally. This paper provides an integrative literature review that focuses on literature related to SCM, Lean and Lean Six Sigma, Industry 4.0, digital transformation and supply chain coordination. The literature has been split into themes so that key findings can be identified. Relationships between research areas have also been identified along with gaps in the literature. The synthesis shows that digital technologies can be used to improve Lean within processes. However, digital technologies do not automatically improve supply chain performance. It depends on how well digital technologies are aligned with process maturity, organisational preparedness, information sharing and continual improvement. A key gap in the research was found to be the absence of an integrated framework that can explain how digital technologies and Lean/Lean Six Sigma can be combined with supply chain coordination to improve operational performance, resilience and sustainability. A conceptual research framework has been proposed along with suggestions for future empirical and modelling research.

Keywords: Supply Chain Management; Lean Supply Chain; Lean Six Sigma; Industry 4.0; Digital Transformation; Supply Chain Coordination; Digital Twins; Operational Performance; Resilience; Sustainability.

1. INTRODUCTION

Supply chain management used to be an operation focused activity, however it now spans many areas including procurement, manufacturing, planning, distribution, customer fulfilment and post sales services. A modern supply chain will include many organisations and it is important to manage the flow of goods, information, funds and decisions. There are two aspects to SCM: design decisions and coordination decisions (Lu and Swaminathan, 2015).

A supply chain needs to not only perform well individually within each organisation, but also ensure good relations between the suppliers, manufacturers, distributors, retailers and customers. Without good coordination there will be issues such as high stock levels, late deliveries, variability in product quality, underutilised resources and inability to respond to changes in demand. Therefore, methods are becoming popular to improve supply chains.

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Lean Manufacturing has been used to improve operational inefficiencies. This includes reducing waste, continual improvements, standardisation, optimising flow and just in time. Lean Supply Chain focuses on applying these principles to the supply chain including suppliers, logistics, distribution and customers. Lean Six Sigma adds structure to reduce waste whilst improving processes. This can be used to improve quality, consistency, delivery and resource usage within the supply chain.

However traditional lean and lean six sigma may be limited due to the complexity and fast paced nature of industry. Data collection can be labour intensive, delays can occur in reporting, the information can be very siloed and analysis can be reactive. This has led to interest in Industry 4.0.

Industry 4.0 provides opportunities to improve visibility throughout the supply chain. Predictive analytics can be used to anticipate disruptions, IoT can be used to monitor production, coordination can be improved with inventory and traceability can be improved. By using IoT to collect data, Artificial Intelligence to analyse data, Digital Twins to create virtual replicas and blockchain to track information between the organisations involved, these technologies could improve lean and lean six sigma practices.

However, there are challenges to overcome. In a study looking at Lean Supply Chain and Industry 4.0, it was found that it was important that the technologies were compatible, standardised, information shared, right culture, continual improvements and lean maturity (Rossini et al., 2024). In another study looking at integrating lean six sigma and industry 4.0, it was found that although there was potential to integrate them there were challenges with the complexity of the technologies, need to train staff, resistance to change and standardisation (Gomaa, 2025).

This shows that digital transformation should not just involve investing in advanced technologies. They must align with processes, management practices and people. Improvements from within individual facilities may not improve the whole supply chain. Therefore, it is important to look at how digital capabilities, lean practices and coordination can be integrated.

1.1 Research problem

The concepts of Lean Supply Chain, Lean Six Sigma, Industry 4.0, digital technologies and coordination within supply chains have been covered in the literature. However, this has not always been done through the same framework. The literature often focuses on the capabilities of digital technologies, whilst Lean literature focuses on reducing waste and improving processes. Coordination literature focuses on information sharing, interdependency, motivation, relationships and collaboration.

This creates an issue where there is not much integration of the different concepts to provide a clear understanding of how digital technologies and Lean practices work together across organisational boundaries to improve supply chain outcomes.

1.2 Aim and objectives

This paper aims to provide an overview of the existing literature regarding Lean Supply Chain, Lean Six Sigma and Industry 4.0. A research agenda will be identified to improve supply chain performance through integration.

The objectives are:

1. To identify the development and key aspects of supply chain management
2. To explain how lean and lean six sigma has contributed to improvements in operations and supply chain
3. To analyse how industry 4.0 can support digital supply chains
4. To identify how organisational structures and coordination will affect integration success
5. To identify a gap in research and propose a conceptual framework to be used for further empirical research.

1.3 Research questions

This review aims to answer the following research questions:

- RQ1: How do Lean and Lean Six Sigma practices help supply chain coordination and performance?
- RQ2: How can Industry 4.0 technologies support Lean practices throughout supply chain networks?

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- RQ3: What are the technological, organisational and coordination factors that can impact the successful integration of practices?
- RQ4: What are the research gaps related to the combined impact of Lean, digital technology, coordination, resilience and sustainability?

2. Review methodology

2.1 Literature Review Approach

An integrated literature review approach has been taken within the paper, this is appropriate due to the research problem encompassing different areas and the aim of the review to provide a conceptual understanding.

Research was sourced from the provided PDF research papers. Research topics include general SCM, Supply Chain Coordination, Industry 4.0, Integration of Lean and Lean Six Sigma, Digital Twins, Blockchain, Digital Threads and Technology Diffusion.

This review can be considered a draft integrated review. In order to conduct a proper systematic literature review this would need to have a database searched with search terms, time frame, duplicates removed, screening logs, inclusion criteria, and a repeatable selection process.

2.2 Theme Grouping

The papers available were grouped into 6 different themes:

- Fundamentals and Evolution of Supply Chain Management
- Supply Chain Coordination and Performance Improvement
- Lean Manufacturing, Lean Supply Chain and Six Sigma
- Industry 4.0 and Digital Supply Chains
- Integration of Lean/Lean Six Sigma and Industry 4.0
- Challenges, Sustainability and Resilience

The grouping of the themes allows for links between the themes to be identified, common findings and where arguments have been made.

2.3 Synthesis Approach

The synthesis involved 4 stages. Firstly, identifying the focus of conceptualisation of each available paper. Secondly, identifying themes and grouping similar papers together. Thirdly, comparing themes to identify how they complement each other, any limitations and overlaps. Lastly, bringing together findings to create a proposed research gap and concept.

The review does not quantify the effect size of each paper. It cannot be said that any one technology provides a quantified performance improvement based on the whole literature. This would require similar results from empirical studies and a more formal method of assessing evidence.

3. FOUNDATIONS OF SUPPLY CHAIN MANAGEMENT

3.1 Evolution and scope of SCM

SCM refers to the planning and coordination of activities involved in sourcing raw materials, selecting suppliers, purchase, planning production, stock control, logistics, distribution, fulfilling demand and sharing information.

Lu and Swaminathan (2015) provide an insight into two key concepts in Supply Chain Management: configuration and coordination. Configuration relates to the design of a supply chain network. This includes understanding where and how different parts of your supply chain are set up. Coordination relates to managing the inter-dependent aspects of the supply chain. Having an optimal configuration can still result in poor performance if there isn’t good sharing of information between those involved in the supply chain.

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Understanding this will be important when looking into digitally enabled manufacturing. Having access to more information using digital technologies may not be effective without a good configuration and coordination within the supply chain.

3.2 Supply Chain Coordination

Supply Chain Coordination is managing inter-dependent activities within the organisations involved in the supply chain in order to improve overall performance. There are many ways to achieve this, including logistics coordination, information sharing, incentives and learning (Mishra and Sharma, 2015). A conceptual model has been created using Six Sigma and Interpretive Structural Modelling (ISM).

Coordination can involve many aspects of the organisation, not just information technology. This can include having a good structure, having common goals, involvement of staff, having trust, having decision making powers, allocating risk and understanding the relationship between your supply chain partners. Having an advanced information system within your supply chain can still result in poor coordination if your supply chain partners don't trust the information, have differing goals or don't have processes in place to utilise the information.

This suggests that coordination should be viewed as a mechanism. Whilst digital tools may give access to information, how the organisation is structured can impact if there is coordination.

3.3 Supply Chain Performance

There are many aspects to consider when looking at supply chain performance. These include:

- Cost and resource efficiency.
- Quality and consistency of product.
- Consistency of delivery and lead times.
- Efficiency of stock and working capital.
- Flexibility and responsiveness.
- Robustness.
- Environmental and resource performance.

These can work together however they can also conflict. For example reducing stock can increase working capital efficiency however this can cause issues with being vulnerable to supply chain disruptions if there are unreliable systems in place to replenish stocks. Automating can increase consistency however this can increase integration costs and reliance on specialist technical skills.

This shows that you shouldn't look at improving your supply chain based on one efficiency measure. Instead a more holistic view should be taken to understand if digitally and Lean interventions result in benefits throughout the supply chain or simply shifting costs and risks between the parties involved.

4. LEAN AND LEAN SIX SIGMA IN SUPPLY CHAINS

4.1 Lean principles and Lean Supply Chain

Lean is a methodology focused on ensuring maximum added value for customers whilst eliminating unproductive processes. Common practices used are continuous improvement, standardisation, just-in-time, visual management, value stream mapping and waste elimination.

By applying lean methodologies within a supply chain, areas such as reliable suppliers, transportation, stock management, information flow, synchronised production and customer delivery will also be improved. This is important as often inefficiencies occur due to the complexity of multiple links and connections.

A lean supply chain involves creating a value stream incorporating people, functions and processes which are operationally linked (Rossini et al., 2024). The analysis outlines that lean supply chain and Industry 4.0 have similar goals to improve efficiency and reduce waste. However, there are opportunities and challenges to implement.

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The lean approach will depend on the particular environment. If there is unpredictable demand, long lead times with suppliers and high product variety, processes may need to be altered. Overall lean is a set of principles and methods to help improve processes.

4.2 Lean Six Sigma

Lean Six Sigma combines lean and six sigma. A key methodology used is DMAIC – define, measure, analyse, improve and control.

Six sigma is a systematic and data driven approach to reducing defects and variation in processes (Mishra and Sharma, 2015). By combining Six sigma with ISM we can see how process improvement methodologies can be used to structure complex coordination issues.

Within a supply chain Lean Six Sigma can help to analyse recurring issues such as late deliveries, incorrect stock levels, defects, supplier quality issues, bottlenecks and inconsistent delivery. The methodology also means there is a structured approach to improvement. This helps businesses to identify performance issues, quantify them, identify possible causes, create improvements and be in control.

However, the effectiveness of lean six sigma depends on the quality and speed of data being available. Causes can be difficult to identify outside of the organisation. If data is slow and fragmented then the DMAIC process may be based on incomplete information.

4.3 Limitations

Traditional improvement programmes can suffer from data being manually collected, only measured in certain departments, analysing past issues and lack of insight into supplier networks. This is made worse as supply chains often involve many partners, changing environments and high frequency data.

Digital technologies can help overcome these issues by automatically collecting data, more frequent monitoring and better analysis. However, if a process is digitised but not redesigned then waste could still remain or even increase. Digital transformation should be implemented alongside process improvement, standardisation and organisational goals.

5. INDUSTRY 4.0 AND DIGITAL SUPPLY CHAINS

5.1 Industry 4.0

Industry 4.0 is the integration of digital technology within manufacture and industry. Benefits to SCM include being able to link different areas such as physical processes, information systems, analytics and decision-making.

The literature shows that benefits of Industry 4.0 include increases in productivity, quality, scheduling, resource utilisation, maintenance, energy efficiency and decision-making (Rossini et al 2024). Other benefits include reduced waste (Rossini et al 2024).

This can be beneficial as it provides useful data across multiple areas of the supply chain. It can improve inventory visibility, production synchronisation, early identification of delays and faster response times.

However, to benefit organisations the data must be accurate enough, systems must be able to share data and organisations must have the capability and authority to make use of the data.

5.2 Internet of Things

The internet of things can provide data from physical objects via a network of sensors and devices. This can be applied within manufacturing and logistics to monitor the condition of machines, track location, monitor temperature, inventory and shipments.

This can provide benefits to Lean and Lean Six Sigma by providing improved data during the Measure phase of DMAIC. This can increase visibility and reduce reliance on manual checks. Continuous monitoring can allow quicker identification of any issues.

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This can also help provide visibility of inventory levels, shipment conditions and critical materials across multiple partners. However, the sensors in place must be reliable, data must be standardised, there must be good connectivity, secure systems must be in place and ownership of data must be agreed.

5.3 Artificial Intelligence and Big Data Analysis

AI and big data analysis can help organisations analyse large amounts of complex data to identify patterns, predict and aid decision-making. This can be applied within supply chains to predict demand, predictive maintenance, quality analysis, optimise inventory and predict disruptions.

Within Lean Six Sigma this can help to improve root cause analysis using analytical tools to identify what conditions within a process are causing defects/delays. Predictive methods can also be used to improve traditional problem solving by predicting the chances of issues arising.

However, there must be high quality data, an appropriate model, easy to understand and continuous verification. Just because a recommendation has been made based on predictive analysis doesn't mean it will improve the performance of the supply chain, it must be operationally viable and match the aims and constraints of the organisations.

5.4 Digital Twins & Digital Threads

Digital twins can be used to monitor, analyse, simulate and support decision-making for a physical item. Within manufacturing this can help to monitor equipment, analyse production systems, plan maintenance and assess different scenarios.

Within Lean this can help to test changes to processes. Scenario analysis can be performed to help with production scheduling, identifying bottlenecks and allocating resources. If the digital twins cover a network of connected processes, then this can help identify the impact of changes to one area.

A digital thread can help ensure that information remains connected throughout the product/system life cycle. This can help ensure relationships between design, engineering, manufacturing, operation and maintenance are maintained. This can be beneficial if decisions need to be made based on traceable product/process information.

However, just because a digital twin exists for a single machine/production line doesn't mean it will cover the whole supply chain. To use this in wider applications appropriate models must be used, data must be connected, standardised and appropriate methods must be put in place to manage uncertainty across multiple organisations.

5.5 Blockchain

Blockchain has been looked at as a way of providing shared information, traceability and ensuring information is accurate. This can be relevant if multiple parties within a supply chain need to record information.

From a Lean perspective this can help to investigate defects, reduce delays in verifying information and improve material visibility. In digitally integrated systems this can complement other systems where there needs to be shared information but each party don't fully have control over the other parties database.

However, issues can arise regarding governance, increased transaction costs, confidentiality, interoperability and the quality of data. Just because information is shared doesn't mean the original information was accurate. Therefore, blockchain should be seen as an enabling tool dependent on the situation.

6. Integration of Lean, Lean Six Sigma, and Industry 4.0

6.1 Complementary capabilities

Lean and Lean Six Sigma focus on delivering value, reducing waste, creating a stable process, measuring and improving. Industry 4.0 adds digital connectivity, data gathering, analysis using computers, automation and simulation. Combining both can help deliver improvement and make decision making more continuous and data driven.

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Gomaa (2025) discusses how Lean Six Sigma 4.0 can be used to combine Lean Six Sigma with new technology such as IoT, AI, digital twin and big data analytics. However, there are issues relating to employee capabilities, organisational push back and the complexity of technology.

Digital tools can help improve the methods but cannot replace the method itself. For example, whilst predictive maintenance could help highlight a machine which is likely to fail, Lean techniques can help look at the overall process of maintenance. This would include looking at parts being available to repair the machine, and any constraints in the schedule.

Similarly, digital tools can help highlight areas of discrepancy in stock levels however to improve this there needs to be clear ownership of stock levels, clear rules in relation to restocking and collaboration across the supply chain.

6.2 Process Maturity

In order to integrate Lean and Industry 4.0 there are several important factors to consider including compatibility, standardisation, IT, culture and continual improvement (Rossini et al, 2024). It is important to consider the maturity of Lean.

This suggests it can be beneficial to have a mature process with clear metrics and data first before adding complicated digital tools. If this isn't done, then automation will simply replicate the inconsistencies created by poor processes. Advanced analytics will give recommendations based on unclear processes.

However, process maturity does not mean that all Lean initiatives need to be implemented first. There may be some digital tools which can help organisations identify waste or improve their metrics. The order and extent to which these are adopted will depend on the issue in operation, process maturity and capability.

6.3 Organisation & Employee

Integrating new technology can be a social/technical issue. Employees need to have knowledge to understand data, use digital tools, improve processes and adapt to changes. Management needs to have clear roles, offer training and encourage collaboration.

Some important factors to consider when implementing LSS 4.0 include up-skilling employees, leaders being committed, collaboration and organisational change (Gomaa, 2025). Especially due to the changes in decision making rights and increased visibility of performance from digital tools.

When integrating digital tools into the supply chain it is important to consider the capability of both the technology and organisation. A firm may have advanced analytics, however without clear governance, skills and relationships with partners they will not be able to make coordinated decisions.

6.4 Interoperability and information sharing

Interoperability involves systems being able to share and utilise information. However, supply chains can have various enterprise systems, multiple data formats and processes. This can cause issues with information sharing.

It is important to ensure partners understand how they are going to share information. They need to have an understanding of what data is to be collected, who has access to information, what their roles are in collecting information, how frequently information will be updated and how much decision making will take place using this information. Having poor data collection processes can create issues where more information is being collected, but it is not properly coordinated.

Looking at coordinating supply chains, Mishra and Sharma (2015) highlight that there are many factors to consider when planning to coordinate. This includes considering the technical, process and people aspects of the system. Using this knowledge and applying it to researching Industry 4.0, it shows interoperability and information governance should be considered.

7. Sustainability and supply-chain resilience

7.1 Sustainability

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Achieving sustainable supply chain operations requires consideration of environmental, economic and social impacts throughout the entire process of sourcing, manufacturing, distributing, using and end-of-life. Lean methods can help improve resource efficiency by reducing waste such as material, motion, inventory, rework, etc.

Industry 4.0 technology can further improve supply chain processes by providing energy monitoring, resource tracking, optimised manufacturing, predictive maintenance and improved product traceability. This link between Lean 4.0, energy efficiency, reduced waste, carbon tracking and circular economy practices are discussed by Gomaa (2025).

However, it is important not to automatically assume that operations will become more sustainable due to increased efficiency. Although less waste would be generated during manufacturing, this can be offset by an increase in energy usage due to digital infrastructure, increased equipment needs and changes to transport and inventory policy. Appropriate metrics must also be used to prove sustainability.

The future research should look at the actual environmental and resource impacts of the supply chain.

7.2 Resilience

Supply chain resilience is the ability to prepare for, resist, adapt to and recover from disruptions that may occur throughout the supply chain including supplier failure, transportation delays, demand shocks, equipment failure and material unavailability.

Improved digital visibility and predictive analytics can assist organisations to identify potential risks and prepare for different scenarios. Lean can also assist by creating standardised methods to solve problems and reduce avoidable inefficiencies within operations. However, if a supply chain is too optimised it can become prone to risk due to low buffer levels, few alternative suppliers and reliance on one technology.

Therefore there can be a balancing act between having a high level of efficiency and resilience. Less stock can reduce holding costs but can limit the time available to react to disruptions. This should be balanced depending on the importance of the material, how uncertain the supply is, the recovery time and the cost of disruption.

The literature suggests that resilience is an important factor to consider in future research however, the provided information does not demonstrate a universally quantifiable relationship between the adoption of Lean 4.0 and supply chain resilience. This needs to be explicitly researched.

8. Critical synthesis of the literature

The reviewed papers suggest several important relationships among SCM, Lean practices, digital technologies, and organizational coordination. Table 1 summarizes the thematic synthesis and the corresponding unresolved questions.

Table 1. Thematic synthesis of the reviewed literature

Research theme	Main contribution	Limitation or unresolved issue
SCM foundations	Distinguishes network configuration from coordination and highlights end-to-end management.	The practical integration of decisions across heterogeneous partners remains context-dependent.
Supply-chain coordination	Identifies information sharing, logistics, incentives, learning, and human factors as relevant mechanisms.	The interaction among coordination mechanisms and digital capabilities needs further integration.
Lean and Lean Six Sigma	Provides methods for waste reduction, variation control, structured problem-solving, and continuous improvement.	Conventional approaches may be constrained by delayed data and fragmented information.

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Industry 4.0	Enables connected data collection, analytical decision support, automation, and simulation.	Benefits depend on data quality, interoperability, implementation costs, and organizational capability.
Lean/Industry 4.0 integration	Identifies potential synergies in productivity, visibility, waste reduction, and process improvement.	There is no universally applicable implementation sequence or framework established by the reviewed sources.
Sustainability and resilience	Broadens performance assessment beyond immediate cost and productivity.	Integrated, measurable evidence connecting digital Lean practices to environmental and resilience outcomes remains a priority for further research.

8.1 Key Themes

There are three key areas where the literature has converged.

Both lean and industry 4.0 seek to improve operational performance. However, lean is focused on providing value, reducing wastage and continuously improving while Industry 4.0 focuses on providing digital connectivity, automating processes, analysing data and making information available. This complementary nature means there is a reason to combine them.

Coordination of the supply chain is a key focus. Sharing information, working together to make decisions, having systems that work together and having aligned goals will determine how digital information can be turned into action.

There is a need for the organisation and its people to have certain capabilities to ensure integration can happen successfully. Providing training, management buy in, mature processes, change management and a culture of continual improvement all affect how well digital tools can be used.

8.2 Areas to consider

There are a few areas to consider.

Is there a cause and effect? Just because there is a digital technology doesn’t mean it will improve the supply chain. Research needs to understand how adopting the technology is different to using it, integrating it into processes, improving coordination and seeing tangible benefits.

Will improvements at a plant level lead to improvements throughout the supply chain? Research should look to understand how the benefits at a plant level are different from those at a supply chain level and if benefits are shared or passed on.

Cost, delivery, flexibility, resilience and sustainability may not all improve. Research needs to look at how these outcomes interact.

The right mix of technologies and lean practices may depend on the size of the organisation, what industry they are in, their digital maturity, uncertainty in the supply chain and the capability of their people. If the framework is to be used widely, it should state what is generic and what needs to be adapted depending on the context.

8.3 Interpretation

The literature suggests that Lean Supply Chain 4.0 should be seen as an integrated approach to operations and the organisation. It has the potential to improve visibility and analysis thanks to digital systems, but structured approaches such as lean or lean six sigma can help to identify and reduce inefficiencies. Coordination will determine if improvements can be applied.

This has led to the research gap and conceptual framework outlined below.

9. RESEARCH GAP AND FUTURE RESEARCH PROPOSITIONS

9.1 Identified research gap

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The principal research gap identified in this review is the lack of an integrated and empirically validated framework explaining how Industry 4.0 technologies and Lean/Lean Six Sigma practices interact through supply-chain coordination mechanisms to influence operational performance, resilience, and sustainability, while accounting for organizational readiness and interoperability.

There are multiple gaps:

1. Integration Gap

While Lean/Lean Six Sigma and Industry 4.0 have been highlighted as supporting one another, there needs to be more detail into how the digital tools integrate with the structured improvement processes.

2. Coordination Gap

Supply chain coordination includes technical, procedural, people and relational factors. There needs to be further research into how these factors act as mediators to the relationship between digital integration and performance at network level.

3. Implementation Gap

Organisations have different levels of digital maturity, lean maturity, financial resources, people capabilities and data availability. This means there are important research questions to answer around the order and performance implications.

4. Performance Measurement Gap

Efficiency, cost, quality, delivery, resilience and sustainability need to be considered together. There needs to be research into the relationship between these outcomes with clear indicators and suitable research design.

5. Validation Gap

Conceptual models are helpful in showing the relationships between factors however they need to be validated in practice within a manufacturing and supply chain environment.

This represents a gap identified from the literature provided. It does not indicate that no previous research has been undertaken into these areas. Claims made need to be validated against a wider body of literature with systematic searching before submission to a journal.

9.2 Proposed conceptual framework

Based on the synthesis, this paper proposes a framework in which digital technology capability and Lean/Lean Six Sigma capability jointly support supply-chain coordination, which in turn influences supply-chain performance.

The framework includes four principal constructs:

1. **Digital technology capability:** The effective use of IoT, AI, big data analytics, digital twins, blockchain, and connected information systems.
2. **Lean/Lean Six Sigma capability:** The application of waste reduction, standardized processes, DMAIC, quality improvement, and continuous-improvement practices.
3. **Supply-chain coordination:** The effectiveness of information sharing, collaborative planning, aligned incentives, interorganizational learning, and coordinated decisions.
4. **Supply-chain performance:** Outcomes covering cost, quality, delivery, flexibility, resilience, and sustainability.

Organizational readiness, workforce competence, process maturity, and system interoperability are proposed as contextual factors that may influence the relationships between these constructs.

Figure 1. Proposed conceptual framework

Digital capability

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(IoT, AI, analytics, digital twins, blockchain)

+

Lean / Lean Six Sigma capability

(Waste reduction, DMAIC, standardisation, continuous improvement)

↓

Supply chain collaboration

(Information sharing, collaborative planning, aligned goals, decision making)

↓

Supply chain performance

(Cost, quality, delivery, flexibility, resilience, sustainability)

Influencing factors: organisational readiness, workforce capability, maturity of Lean, data quality and compatibility.

This framework is conceptually based and not empirically tested in this paper. It will help to guide research design in the future.

9.3 Proposed research propositions

The following propositions are supported:

- **P1:** There will be a positive relationship between digital technologies capabilities and supply chain coordination due to having information that can be shared, trusted and used.
- **P2:** Having higher lean/lean six sigma capabilities will lead to an increase in operational performance due to reduced waste, improved consistency and continual improvement.
- **P3:** There will be a mediating relationship between digital technologies capabilities and supply chain performance via supply chain coordination.
- **P4:** Having both digital technologies and lean/lean six sigma capabilities will lead to improved operational performance compared to having just one capability.
- **P5:** Organisational readiness, employee capabilities, process maturity and interoperability will affect the relationship between digital integration and supply chain performance.
- **P6:** The relationships between lean supply chain 4.0 practices and overall performance will vary depending on whether it is cost, quality, delivery, resilience or sustainability.

  These are hypotheses that would need to be investigated in the future.

9.4 Recommended empirical validation

This can then be developed within a mixed methods approach.

Phase one could involve a semi-structured interview approach with supply chain managers, manufacturing engineers, quality professionals, digital transformation experts and technology providers to define constructs further and establish how coordination is carried out within the context of the organisation.

Phase two could involve creating a survey of manufacturing organisations where digital maturity, Lean/Lean Six Sigma maturity, coordination within supply chains, organisational readiness and performance can be measured. If there is an appropriate sample size, with good measurement properties, structural equation modelling could be considered.

An additional case study could look at the implementation of digital monitoring and lean improvement practices within a manufacturers supply chain and production processes. This could measure performance metrics such as

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defect rates, lead time, on time delivery, stock accuracy, unplanned downtime, energy used and time to recover from disruptions.

By having longitudinal data we can look at how these measures have changed over time accounting for other changes. This would give more evidence than purely looking at manager's perceptions of improvement.

10. IMPLICATIONS FOR MECHANICAL AND INDUSTRIAL ENGINEERING

This area of research is particularly relevant to mechanical and Industrial engineering as it looks at the interplay between various elements within a manufacturing process. These elements include physical processes, machinery, materials flow, planning, maintenance, quality assurance and logistics.

With Digital Twins and IoT sensors we are able to monitor aspects of the manufacturing process. Lean and Lean Six Sigma can be used to interpret issues within the operation and enable systematic improvements. This combination can be explored within a manufacturing process such as machining, assembly, materials handling, maintenance and scheduling.

An example of this could be using digital monitoring within the cell to provide real time data on machine utilisation, cycle times and quality issues. Then with lean analysis we can look at where the bottlenecks and non-value-added activities are. At the supply chain level working with suppliers and logistics will enable us to ensure improvements to manufacturing are reflected in the supply chain by improved reliability.

As this is an engineering project the contribution should go into more detail than just what a manager would do. A good follow up to this project would be to define specific variables, explain how this works within the operation, define the boundaries of the system and prove the relationships using data from within the manufacturing or supply chain.

11. FUTURE RESEARCH DIRECTIONS

There are several areas to consider:

Build on this work by providing clarity and transparency in any future reviews by ensuring a clear, repeatable methodology is provided including a discussion on the sources searched; databases, keywords, screening and quality assessment. This will provide insight into whether the integration gap identified is still an issue within literature.

Empirical work looking at the underlying drivers of the link between digital technologies and performance. The focus should not just be on technology usage but also include the actual usage of systems, quality of information, decision-making delays, process changes and improvements in collaboration.

Investigate how different organizations with varying degrees of Lean maturity and digital maturity implement these improvements. This can provide further understanding on when it is most appropriate to focus on standardizing processes before implementing them and when digital technologies can aid improvement.

Investigate the impacts of working with other organisations. This includes interoperability, data governance, security and collaboration. This will be particularly important if data is being shared between different organisations.

Future work should look at the trade-off between performance criteria such as efficiency, resilience and sustainability. Depending on the research questions and data available methods such as multi-objective optimisation, discrete-event simulations, digital twin modelling and longitudinal case studies may be appropriate.

Consider the impact on people and organisational factors. This could include training staff, staff involvement, accountability for decision making and learning within the organisation. This may affect whether technical solutions result in long term performance improvements.

12. CONCLUSION

This paper provides a synthesis of the current literature on Supply Chain Management, Lean and Lean Six Sigma, and Industry 4.0, with regards to digital supply chain integration. It can be concluded that there are structured

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process improvement techniques available within Lean and capabilities to connect, monitor, analyse, automate and simulate processes using Industry 4.0 technologies. These can be coordinated within the supply chain.

The literature shows that factors such as process maturity, interoperability, employee capability, organisational culture, management support and information sharing can impact how integration will be achieved. Improving efficiency does not automatically result in improved resilience and sustainability; it needs to be measured explicitly.

A key knowledge gap identified was the need for an integrated framework to show how capabilities from digital technologies and Lean/Lean Six Sigma affect supply chain coordination and performance across multiple dimensions. This framework and research propositions can be used as a foundation to investigate the topic further in manufacturing and industrial engineering.

This paper provides a structured synthesis and research agenda. However, findings should be considered with the initial scope of the literature review in mind. The methodology should be made replicable prior to submission of the review. All 25 papers should be analysed and references checked against the original publication. The knowledge gap should be assessed against other relevant studies.

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