Unlocking the potential: empirical analysis of enablers, barriers, benefits and technologies for integrating Industry 4.0 and Lean Six Sigma in manufacturing organisations

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Abstract

Purpose: The integration of Lean Six Sigma and Industry 4.0 is in the nascent stage and promises to achieve new optimums in operational excellence. This study aims to empirically examine the enablers, barriers, benefits, and application of Industry 4.0 technologies in Lean six Sigma and Industry 4.0 integration.

Design/Methodology/Approach: A pilot survey was chosen as an appropriate methodology, as Lean six Sigma and Industry 4.0 integration is still budding. The survey targeted senior quality management professionals, quality managers, team leaders, Lean Six Sigma Black Belts, and operations managers to collect the relevant research data. The questionnaire was sent to 200 respondents and received 53 valid responses.

Findings: This study reveals that "top management support" is an essential enabler for Lean Six Sigma and Industry 4.0 integration. The most significant barrier was "poor understanding of data analysis" and "lack of top management support". The findings further illustrated that Lean Six Sigma and Industry 4.0 integration resulted in greater efficiency, lower operational costs, improved productivity, improved customer satisfaction, and improved quality. Regarding Industry 4.0 technology integration at different phases of Lean Six Sigma, we noticed that Big Data Analytics and Artificial Intelligence are the most prominent technologies used in all phases of Lean Six Sigma implementation.

Originality/value: Lean Six Sigma and Industry 4.0 integration was studied at a conceptual level. This is the first empirical study targeted toward understanding the Lean Six Sigma and Industry 4.0 integration. In addition, this study investigates the application of widely used Industry 4.0 technologies in different phases of Lean Six Sigma.

Practical Implications: The outcomes of this study can be useful for organisational managers to understand the enablers and barriers before integrating Lean Six Sigma and Industry 4.0 for adoption in their organisations. Secondly, it helps to convince top management and human resource personnel by providing a list of benefits of Lean Six Sigma and Industry 4.0 integration.

Finally, it can help decision-makers understand which Industry 4.0 technologies can be used in different stages of Lean Six Sigma methodology.

Research limitations/implications: One of the limitations of this study is the sample size. Lean Six Sigma and Industry 4.0 are emerging concepts; hence, obtaining a larger sample size is difficult. In addition, the study used non-parametric tests to analyse the data. Therefore, future studies should be conducted with large sample sizes across different continents and countries to understand differences in the key findings.

Keywords: Lean Six Sigma**;** Industry 4.0; I4.0 Technologies; Barriers; Enablers; Benefits

1. Introduction

Lean Six Sigma (LSS) combines Lean Manufacturing and Six Sigma principles to improve business processes and reduce waste. It focuses on the elimination of defects and variation in order to improve efficiency and quality (Antony, Snee, *et al.*, 2017; Antony, Lancastle, *et al.*, 2023; George and George, 2003; McDermott *et al.*, 2022a; Snee and Hoerl, 2007). By analysing data and using statistical tools, LSS aims to identify and remove the root causes of problems. The methodology also emphasises the importance of involving employees in the process and promoting a culture of continuous improvement (Bhat et al., 2023; McDermott et al., 2022b). Ultimately, LSS seeks to create a more streamlined and effective organisation that can deliver higher-quality products or services while reducing costs and improving customer satisfaction (Antony et al., 2017).

Industry 4.0 (I4.0), also known as the fourth industrial revolution, is a term that originated in Germany in 2011 (Nascimento et al., 2019). It refers to the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and big data analytics into industrial processes (Ciano *et al.*, 2021; Dalenogare *et al.*, 2018). The rise of I4.0 brings the transformation of producing and manufacturing products using machines through robots in smart factories (Antony, Sony, McDermott, *et al.*, 2021; Sony, 2020a). The goal of I4.0 is to transform industrial manufacturing through digitalisation and exploit the potential of new technologies (Rossini et al., 2021). Implementing I4.0 will enable individualised and customised products in a flexible production system. This integration aims to create "smart factories" that are more flexible, efficient, and responsive to customer needs. I4.0 also involves using cyber-physical systems, which enable machines and systems to communicate and make decisions autonomously (Antony, Sony and McDermott, 2021; Sony, 2020b). This transformation is expected to revolutionise the manufacturing industry by improving productivity, quality, and safety while reducing costs and environmental impact (Antony et al., 2023).

The integration of LSS and I4.0 is the need of the hour because it combines the best practices of process improvement and advanced technologies to create a more efficient and effective manufacturing environment (Antony *et al.*, 2022; Nascimento *et al.*, 2019; Rifqi *et al.*, 2021). By integrating LSS and I4.0, companies can leverage the benefits of both methodologies to create a more flexible, efficient, and responsive manufacturing environment (Antony *et al.*, 2022; Bhat *et al.*, 2021). Combining process improvement and advanced technologies allows companies to reduce waste and defects and adapt quickly to changing customer demands and market conditions. This integration ultimately leads to better-quality products, reduced costs, and improved customer satisfaction (Kaswan et al., 2023; Sordan et al., 2022).

LSS and I4.0 complement each other in several ways to improve the quality of products and processes. Firstly, LSS provides a methodology for identifying and eliminating waste, variability, and defects in manufacturing processes (Antony, 2015; Antony, Snee *et al.*, 2017; Bhat *et al.*, 2021). It emphasises the importance of continuous improvement and employee involvement in process improvement. This approach aligns well with I4.0's focus on optimising processes using advanced technologies such as automation, sensors, and data analytics (Kaswan et al., 2023; Sordan et al., 2022). Secondly, I4.0 technologies enable real-time monitoring and data collection, which can be used to identify defects and process deviations. These technologies can provide insights into the root causes of defects and enable predictive maintenance, reducing the likelihood of equipment failure and quality issues (Bhat et al., 2021; Ganjavi and Fazlollahtabar, 2022). Thirdly, LSS emphasises the importance of data-driven decision-making and statistical analysis to identify the root causes of defects and variability. I4.0 provides the tools to collect, process, and analyse vast amounts of data, which can be used to make more informed decisions about process improvement (Chiarini and Kumar, 2021; Tissir et al., 2023).

Understanding the enablers of LSS and I4.0 integration within manufacturing organisations is essential to ensure the effective deployment and sustainment of quality initiatives in disruptive technologies. Also, critical analysis of these enablers can help organisations identify areas where they may need to invest resources, training, and infrastructure to integrate LSS and I4.0 successfully (Bhat et al., 2023; Rana and Jani, 2023). Finally, by addressing these enablers, organisations can improve their ability to implement these methodologies effectively and realise the benefits of improved quality, reduced costs, and improved customer satisfaction (Antony, Snee et al., 2017; Sony et al., 2020).

Besides, comprehending and determining the barriers to integrating LSS and I4.0 within the manufacturing organisation is crucial because these approaches improve efficiency, productivity, and competitiveness (Antony, Sony *et al.*, 2023; Sony, Antony, Douglas, *et al.*, 2021). Suppose an organisation cannot integrate these approaches effectively. In that case, it may miss significant benefits, such as cost reduction, innovation, and higher-quality products. By identifying and addressing the barriers to integration, organisations can unlock the full potential of LSS and I4.0, which can lead to higher levels of success in today's highly competitive manufacturing industry (Kaswan et al., 2023; Sordan et al., 2022). Therefore, understanding these barriers is crucial to stay competitive and achieving sustained success.

At the same time, research and analysis of I4.0 technology are essential for effective integration with LSS because they can help organisations identify opportunities for improvement, overcome challenges, ensure compatibility, and achieve maximum benefits (Sony, 2020b). By understanding the latest technologies and how they can be integrated with LSS, organisations can identify new ways to optimise their processes and products. Also, integrating I4.0 technology with LSS can be challenging due to the complexity of the technology and the need for a deep understanding of both approaches (Antony, Sony, et al., 2023; Chiarini and Kumar, 2021). The in-depth study can help organisations overcome these challenges by providing insights into best practices, common pitfalls, and solutions to common integration problems (Sader et al., 2022). Moreover, I4.0 technology is constantly evolving, and ensuring that the technology used is compatible with LSS methodologies is essential. Therefore, the analysis can help organisations identify the most appropriate technologies and ensure they are compatible with LSS principles. Eventually, more effective research can help organisations identify the most effective ways to integrate these approaches to achieve maximum benefits (Tissir et al., 2023; Vinodh et al., 2020).

However, there is a lack of empirical studies focusing on integrating LSS and I4.0, especially from the perspective of enablers, berries, benefits and technology (Antony et al., 2023; Sordan et al., 2022; Tissir et al., 2023). Thus, the study aims to empirically unearth critical factors of LSS and I4.0 integration, such as enablers, barriers, Benefits and Technology. The following are the research questions (RQs) articulated to answer the research objective effectively.

RQ1: What are the enablers and barriers of LSS and I4.0 integration within manufacturing organisations?

RQ2: What are the main benefits of integrating I4.0 and LSS?

RQ3: Which I4.0 technology can be integrated and effectively used in Lean and Six Sigma?

The article is structured as follows. The literature review is presented in Section 2, and Section 3 delineates the research methodology adopted for the present study. The results and discussions are presented in Section 4. Section 5 provides the theoretical implications, and Section 6 delineates the managerial implications. Finally, the conclusions, limitations and directions for further research are presented in Section 7.

2. Literature review

The literature is reviewed from the following four perspectives: (i) Integration of I4.0 and LSS, (ii) Enablers of I4.0 and LSS, (iii) Barriers of I4.0 and LSS, (iv) Benefits of I4.0 and LSS integration (v) Tools that enable I4.0 and LSS integration, and (vi) LSS and I4.0 technologies with DMAIC framework.

2.1. Integration of I4.0 and LSS

I4.0 is known as the fourth industrial revolution and is sometimes nominated as smart manufacturing, digital manufacturing, or intelligent manufacturing. The I4.0 technology makes current manufacturing processes more agile, flexible, and smart to fulfil the expectation of the global market (Zhong et al., 2017). LSS is a combined methodology (i.e., integration of Lean manufacturing and Six Sigma) consisting of powerful tools that eliminate waste and variability from the process (Albliwi, 2014; McDermott et al., 2022). Anass et al. (2019) studied the relationship between LSS and I4.0 and found the relation was synergic and compatible. Integrating I4.0 and LSS provides several benefits and meets the current market's expectations. Therefore, the manufacturing organisation should shift their production and distribution mechanism per the emerging trends. The goal of LSS can be achieved much faster by using digitalised tools and techniques such as mobile technology, robotics, the IoT, AI, machine learning, etc. (Kumar et al., 2021). However, it has been noticed that few authors have integrated LSS and I4.0 to assess the synergic benefits. Gupta et al. (2020) investigated how BDA helps predict fast decisions in each stage of the LSS methodology. Vinodh et al. (2021) investigated the synergic benefits of continuous improvement strategies and the application of I4.0 to ensure significant improvements. Similarly, Arcidiacono and Pieroni (2018) proposed the integrated LSS and I4.0 concept in the healthcare sector to optimise the service process and minimise waste, thereby improving the patient's quality of experience.

Integrating I4.0 technologies with LSS facilitates high-level benefits that improve organisational performance (Kumar et al., 2021). Automation and digitalisation can help reduce lead time and cost, benefiting the organisation and its customers. Further, technological advancement and changes in the process enhance employee knowledge, and change management strategy improves their morale. According to Kamble et al. (2018), Lean manufacturing practices facilitate overcoming barriers to the I4.0 implementation process in an organisation. Besides, the challenges associated with Lean Manufacturing implementation can be overcome by successfully adopting digitalised technologies. Apart from the benefits of integrating I4.0 technologies with LSS, some barriers always hinder and destroy the successful implementation process. Conversely, it could always be seen that some factors act as enablers and help implement the concerned approach in the organisation. The following sub-sections discuss the associated enablers, barriers, and benefits of I4.0 technologies with LSS.

2.2. Enablers of I4.0 and LSS

Enablers work as drivers for adopting I4.0 and LSS, which is also necessary for the success of these integrated approaches (Anass et al., 2019; Macias-Aguayo et al., 2022). Enablers are essential elements of organisational strategy that indirectly impact performance while guiding toward success (Alkarney and Albraithen, 2018). These also facilitate organisations to increase the chances of LSS 4.0 implementation success (Vinodh et al., 2021; Gupta et al., 2020). Once enablers are identified according to their importance, it would be easier for managers, decision-makers, and planners to concentrate on them to implement LSS 4.0 in the organisations successfully.

Jayaram (2016) considered understanding data mining, data analysis, and optimisation techniques with I4.0 as critical enablers for LSS and I4.0 implementation. Kim et al. (2017) suggested that investment in training and education, multi-talented personnel, employee involvement, top management support, and alignment of organisational strategy are the key drivers for implementing Six Sigma 4.0 in the organisation. Júnior et al. (2018) highlighted that integration of I4.0 and Lean and training and education on I4.0 technologies are the drivers for successfully adopting I4.0 and Lean methodologies in any organisation. Finally, Gupta et al. (2020) suggested that top management support, big data and dynamic data use, and integration of big data and statistical process control are the key drivers for LSS 4.0 implementation in manufacturing industries. The list of enablers identified from the literature is discussed in Table 1.

Table 1: Enablers of LSS and I4.0 from the literature (Source: Author Constructed)

Enablers	**Authors cited**
Investment in training and education on I4.0. technologies	Kim et al. (2017); Júnior et al. (2018); Macias-Aguayo et al. (2022)
Multi-talented personnel	Kim et al. (2017); Khanzode et al. (2021); Perera et al. (2021); Bhat et al. (2021b)
Top management involvement and support	Perera et al. (2021); Macias-Aguayo et al. (2022); Kim et al. (2017); Gupta et al. (2020)
Involvement of employees and other stakeholders	Macias-Aguayo et al. (2022); Bhat et al. (2021b); Kim et al. (2017)
Integrating Big Data and Voice of Customers	Arcidiacono and Pieroni (2018); Perera et al. (2021)
Combining of integration technology with business strategies	Macias-Aguayo et al. (2022); Perera et al. (2021)

Enablers	Authors cited
Subsidies and seed feeding	Macias-Aguayo et al. (2022)
Understanding of data mining, data analysis and optimisation techniques with I4.0.	Jayaram (2016); Perera et al. (2021)
Alignment of organisational strategies with I4.0. and Lean or LSS	Perera et al. (2021); Kim et al. (2017); Gupta et al. (2020)
Big data and dynamic data use	Gupta et al. (2020)
Understand the synergy of I4.0., Lean, or LSS technologies	Vinodh et al. (2021)
Integration of big data and statistical process control	Gupta et al. (2020)
Ensuring that customer engagement	Sodhi (2020); Perera et al. (2021); Bhat et al. (2021b)
Optimising the use of resources	Sodhi (2020)
Use of Big data to measure and analyse phase	Johansson (2019)
Technical support and people empowerment	Perera et al. (2021); Bhat et al. (2021b)
The dynamic involvement of stakeholders and continuous feedback through IoT	Arcidiacono and Pieroni (2018); Perera et al. (2021); Bhat et al. (2021b)
Integration of I4.0. and DMAIC phase	Dogan and Gurcan (2018)
Integration of I4.0. and LSS	Júnior et al. (2018); Vinodh et al. (2021)

2.3. Barriers of I4.0 and LSS

Barriers act as hurdles and may affect the implementation success of any continuous improvement (CI) initiatives (Opoku Appiah and Abor, 2009). However, the adoption failure of CI initiatives has a negative impact on organisational performance. Therefore, organisational managers should focus on barriers before implementing CI initiatives (Swarnakar et al., 2020). The outcome of the literature review observed several barriers related to I4.0 and LSS approach. For instance, Dogan and Gurcan (2018) highlighted that the lack of Intelligent monitoring and automation systems, a lack of comprehensive understanding of data analysis, and poor knowledge of modelling with I4.0 and LSS are the top three barriers to LSS and I4.0 adoption in an organisation. Johansson (2019) considered a lack of comprehensive understanding of data analysis, poor prevention and resolution of problems through AI technology, a lack of ecosystem, infrastructure, and funds to deploy I4.0 and LSS as critical barriers to LSS and I4.0 adoption. Sodhi (2020) stated that poor knowledge of modelling of I4.0 and LSS, lack of risk assessment, lack of organisational policies, lack of framework/ roadmap for the deployment, and poor integration of I4.0 and LSS for system design are the most critical barriers affecting the LSS and I4.0 implementation in the organisation. The list of barriers identified from the literature is provided in Table 2.

Table 2: Barriers of LSS and I4.0 from the literature(Source: Author Constructed)

Barriers	Authors cited
Lack of real-time visualisations and communications	Jayaram (2016)
Difficulty in data collection from sensors (IoT)	Kim et al. (2017); Gupta et al. (2020)
Lack of Intelligent monitoring and automation system	Jayaram (2016); Dogan and Gurcan (2018)
Poor connection among production processes	Jayaram (2016)
Lack of comprehensive understanding of data analysis	Kim et al. (2017); Johansson (2019); Dogan and Gurcan (2018)
Poor prevention and resolution of problems through AI technology	Kim et al. (2017); Johansson (2019)
Lack of security and reliability of data	Gupta et al. (2020)
Poor knowledge of modelling with I4.0. and LSS	Dogan and Gurcan (2018); Sodhi (2020)
Lack of top management support and poor organisational strategies	Vinodh et al. (2021); Bhat et al. (2021b); Gupta et al. (2020)
Lack of risk assessment	Sodhi (2020)
Difficulty in the cultural transformation to use of I4.0. and LSS	Gupta et al. (2020); Júnior et al. (2019)
Lack of process optimisation through technology	Kim et al. (2017)
Sustaining control and conducting the experiments in its application	Gupta et al. (2020); Bhat et al. (2021b)

Barriers	Authors cited
Lack of Organisational policies	Sodhi (2020)
Lack of framework/ roadmap for the deployment	Vinodh et al. (2021); Bhat et al. (2021b); Sodhi (2020)
Lack of ecosystem, infrastructure and funds to deploy I4.0. and LSS	Johansson (2019); Arcidiacono, and Pieroni (2018)
Poor integration of I4.0. and LSS for system design	Gupta et al. (2020); Sodhi (2020)

2.4. Benefits of I4.0 and LSS integration

Adopting integrated LSS and I4.0 technologies has been reported to be more efficient in customising processes, products, and services, bringing flexibility in the process and better cost mapping and creating value (Kiel et al. 2017). Implementing LSS 4.0 in any manufacturing organisation improves product quality and productivity. It improves the use of resources through automation and digitalisation (Oesterreich and Teuteberg, 2016). In process inventory, defects, and rejects are also reduced due to implementing Lean tools and automating processes (Sodhi 2020; Khanzode et al. 2021). Customer satisfaction is increased by adopting new business models and creating a new value-creation system (Kiel et al. 2017). Adopting digitalised tools and techniques improves decision quality and duration by strengthening intelligent systems, ensuring traceability and process transparency. This integrated approach assists in unearthing bias, ensuring robust prediction, and providing feedback with solutions (Antony et al., 2022). It also helps to minimise the cost of poor quality by reducing expensive and excessive inspection, quality assurance, and reliability problems (Antony et al., 2021). The list of benefits of LSS and I4.0 adoption in the manufacturing environment are provided in Table 3.

Table 3: Listed benefits in the literature(Source: Author Constructed)

Benefits	Authors cited
Lowering operational costs	Khanzode et al. (2021); Jayaram (2016); Gupta et al. (2020)
Better business performance	Perera et al. (2021); Arcidiacono and Pieroni (2018); Júnior et al. (2018)

Benefits	Authors cited
Reduction in WIP Inventory	Khanzode et al. (2021); Gupta et al. (2020); Johansson (2019)
Productivity improvement	Khanzode et al. (2021); Sodhi (2020); Dogan and Gurcan (2018); Júnior et al. (2018); Kim et al. (2017)
Bring LSS and I4.0 culture	Perera et al. (2021); Júnior et al. (2018); Gupta et al. (2020)
Greater efficiency	Khanzode et al. (2021); Dogan and Gurcan (2018)
Increase in overall equipment efficiency (OEE)	Khanzode et al. (2021); Gupta et al. (2020); Dogan and Gurcan (2018)
Reduction in cost of service delivery	Khanzode et al. (2021); Dogan and Gurcan (2018)
Increased customer satisfaction	Khanzode et al. (2021); Arcidiacono, and Pieroni (2018); Perera et al. (2021); Sodhi (2020)
Improve service quality	Khanzode et al. (2021); Perera et al. (2021); Gupta et al. (2020)
Energy usage reduction	Khanzode et al. (2021); Sodhi (2020); Johansson (2019)
Increase in business or creation of new business	Khanzode et al. (2021); Gupta et al. (2020)
Reduction in defects and rejection rate	Khanzode et al. (2021); Gupta et al. (2020); Dogan and Gurcan (2018)
Lead time reduction	Khanzode et al. (2021); Vinodh et al. (2021)
Increased throughput	Khanzode et al. (2021); Gupta et al. (2020)
Leadership Engagement	Perera et al. (2021); Kim et al. (2017)

2.5. Tools that enable I4.0 and LSS integration

I4.0 involves the integration of advanced technologies such as artificial intelligence, the Internet of Things (IoT), Big Data and cloud computing into manufacturing processes. The tools and techniques of I4.0 can be used to enable LSS by providing real-time data and insights that can be used to optimise processes and improve efficiency (Gupta et al., 2020; Perera et al., 2021). Some of the key tools and techniques of I4.0 that LSS are as follows (Arcidiacono and Pieroni, 2018; Azeem et al., 2022; Bhat et al., 2021b; Psarommatis, 2021; Sordan et al., 2022).

- IoT: Sensors can gather real-time data on machine performance, product quality, and other vital metrics. This data can then be used to identify areas for improvement and make data-driven decisions.
- Big Data Analytics: The large amount of data generated by IoT sensors and other sources can be analysed using advanced analytics techniques such as machine learning and predictive analytics. This can help identify patterns and trends that would be difficult to detect using traditional methods.
- Digital Twin: A digital twin is a virtual replica of a physical product or process. It can simulate different scenarios and optimise processes before implementing them in the real world.
- Robotics and Automation: Robots and other automated systems can perform repetitive or dangerous tasks, reducing the risk of errors and improving efficiency.
- Augmented Reality: Augmented reality (AR) technology can provide workers with real-time information about processes and equipment, improving productivity and reducing errors.
- Cloud Computing: Cloud computing can store and process large amounts of data, making it easier to access and analyse.

By using these tools and techniques, organisations can optimise their processes and reduce waste, improving the efficiency and quality of their operations. This can help them achieve LSS goals and stay competitive in the ever-evolving manufacturing landscape.

2.6 LSS and I4.0 technologies with DMAIC framework

The Define-Measure-Analyze-Improve-Control (DMAIC) framework is a problem-solving approach widely used in LSS to improve processes and optimise operations. The DMAIC framework is significant for several reasons. First, it provides a structured and systematic approach to problem-solving, allowing organisations to identify and address issues efficiently and effectively. Second, it promotes data-driven decision-making, ensuring solutions are based on objective evidence rather than assumptions or intuition. Finally, it supports continuous improvement, helping organisations to identify and implement ongoing improvements to their processes and operations (Noronha et al., 2023; Antony et al., 2016).

In the context of I4.0, the DMAIC framework is particularly relevant as it supports integrating advanced technologies such as big data analytics, machine learning, and artificial intelligence. By using these tools to collect and analyse data, organisations can gain deeper insights into their processes and identify areas for improvement more quickly and accurately (Chiarini and Kumar, 2021). Additionally, the DMAIC framework can help organisations effectively manage the complexity and interconnectedness of I4.0 systems, ensuring they operate smoothly and efficiently (Bhat et al., 2021b).

3. Research methodology

The research methodology was a survey approach to answer the questions in the introduction section. Survey research is "the collection of information from a sample of individuals through their responses to questions" (Check and Schutt, 2011). Survey research has several advantages, including its ability to gather large amounts of data quickly and efficiently and its flexibility in allowing researchers to ask a wide range of questions(Ponto, 2015). Surveys can also be administered in various formats, including online, by mail, by phone, or in person. Additionally, survey research can help identify patterns and trends in data that might not be apparent through other methods. (Park and Park, 2016; Ponto, 2015). This study investigates the enablers, barriers, benefits, and I4.0 technologies for LSS and I4.0 integration.

In an emerging research area, the respondents' viewpoints on the same aspect must be structured. Therefore, pilot survey research is appropriate (Zhang et al., 2016). Thus, LSS and I4.0 integration is also an emerging topic; hence, a pilot survey would better gather the relevant data from respondents and help them understand its basics. Further, it will provide the direction for future research (Zhang *et al.*, 2016). To collect the relevant data, this survey targeted senior quality management professionals, quality managers, team leaders, LSS Black Belts, and operations managers. One of the critical aspects of survey research is the design of the questionnaire, which will determine the reliability and validity of the results obtained from the study (Creswell and Poth, 2016; Welman *et al.*, 2005). The enablers, barriers, benefits, and technologies were collated from published studies. The questionnaire was specifically designed for this study based on the literature review. The survey questionnaire is divided into two parts.

The first part aimed to obtain general information about the respondents and their organisations. The second part was devoted to collecting information on various aspects of I4.0 and LSS implementation. The second part also consisted of several enablers, barriers and tools identified from the literature review. The seven-point Likert scale (i.e., where 1 stands for "Strongly Disagree" and 7 for "Strongly Agree") was used to map the responses. The main benefit of a seven-point Likert scale over a five-point Likert scale is that it allows for more significant differentiation and granularity in responses. With seven response options, respondents have more degrees of agreement or disagreement, which can result in more nuanced and accurate data. (Allen and Seaman, 2007; Jaeschke *et al.*, 1990; Sullivan and Artino Jr, 2013).

To check the consistency and accuracy of questions, the developed questionnaire was first piloted with five practitioners and five academicians with experience in both LSS and I4.0. Then, the comments and collegial feedback received from the experts were adopted to revise the questionnaire; this feedback helped simplify some questions to increase the readability. Finally, the revised questionnaire was presented to those experts for their final approval to distribute among respondents. After approval, the survey questionnaire was piloted among targeted respondents using a popular online survey platform "SurveyMonkey". This online platform provides custom survey URLs that are easier for respondents to access the link (Abd Halim *et al.*, 2018; Varela *et al.*, 2016).

Further, it has a customisable feature, which helps to create a visually appealing survey (Abd Halim *et al.*, 2018). Also, the survey can be very interactive, which helps to increase the response rate (Rice *et al.*, 2017). In addition, the online survey will help obtain a large amount of information on the particular field from the respondents in the shortest possible time (Fielding *et al.*, 2008). This survey targeted professionals working in manufacturing and service industries within the United Kingdom, the Netherlands, Brazil, India, Pakistan, and the UAE. These countries were chosen 1) because LSS and I4.0 are implemented in these countries and 2) to get an adequate representation of developed and developing countries. The questionnaire was sent to 200 respondents and received 59 responses over six months. Fifty-three valid responses were available for final analysis. Therefore, the response rate of this survey was 27 %. Easterby-Smith *et al.* (2012) suggest that a survey response above 20% is acceptable. Similar low responses are also noted in previous studies(Lauber *et al.*, 2005; Lee, 2010; Sax *et al.*, 2003) and a low response rate is expected when the topic is an emerging research area. The details of the respondents and demographics are provided in Table 4.

Table 4: Sample Demographics(Source: Author Constructed)

	LE	**SME**	**Grand Total**
Manufacturing Sector	**24**	**8**	**32**
Developed Countries	**13**	**6**	**19**
Experience of respondents (Above five years)	9	3	12
Experience of respondents (Less than five years)	4	3	7
Developing Countries	**11**	**2**	**13**
Experience of respondents (Above five years)	6	1	7
Experience of respondents (Less than five years)	5	1	6
Service Sector	**16**	**5**	**21**
Developed Countries	**11**	**4**	**15**
Experience of respondents (Above five years)	7	1	8
Experience of respondents (Less than five years)	4	3	7
Developing Countries	**5**	**1**	**6**
Experience of respondents (Above five years)	1		1
Experience of respondents (Less than five years)	4	1	5
Grand Total	**40**	**13**	**53**

Table 4 discusses the sample demographic of Large Enterprises (LE) and Small and Medium-scale enterprises (SMEs). LE's had an employee size of more than 250 employees while more than 10 employees and up to 249 employees were classified as SMEs (Loecher, 2000; Page and Söderbom, 2015). Similarly, developed and developing countries were classified based on the OECD classification (OECD, 2021). The data were tested for normality using Anderson-Darling test. This test was used because, for small sample sizes, this test is more sensitive to all types of deviations from normality (Nelson, 1998; Razali *et al.*, 2011). As the data was found to be non-normal with a p-value less than 0.05, a non-parametric test, specifically an independent sample Mann-Whitney U test, was used to assess the differences in enablers and barriers between LE's and SMEs, as well

as between developed and developing countries and the manufacturing and service sectors. The Mann−Whitney *U* test is equivalent to the parametric student t-test for independent samples (MacFarland and Yates, 2016; McKnight and Najab, 2010). These tests have similar purposes used to determine if there are any statistically significant differences between the groups (Milenovic, 2011). It is typically used for ordinal data (McKnight and Najab, 2010).
Further, the I4.0 technologies and their integration with various phases of DMAIC were analysed through frequency analysis. Moreover, Fisher's exact test for two sample proportions (Carr, 1980; Fisher *et al.*, 2011) was used to test the difference in proportions of I4.0 technologies across sectors, company size and economies. The detailed analysis and outcomes are discussed in the next section.

4. Results & Discussion

The study's results are presented below. First, enablers are analysed, followed by barriers and benefits. Lastly, an analysis of integrating I4.0 technologies in DMAIC phases is provided.

4.1. Enablers

A mean analysis was conducted to investigate the enablers in LSS and I4.0 integration for the organisation and whether they differ across sectors, size of organisation & economies. The results are tabulated in Table 5.

Table 5: Enablers of LSS and I4.0 integration(Source: Author Constructed)

Enablers	Sector			Type of Org.		Country	
	Overall	Manuf.	Service	LE	SME	Developing	Developed
Top management support	6.13	6.19	6.05	6.00	6.54	6.05	6.18
Training on I4.0. technologies	5.45	5.50	5.38	5.50	5.31	5.42	5.47
Multi-skilled or multi-talented personnel	5.66	5.63	5.71	5.73	5.46	5.74	5.62
Alignment of organisational strategies with I4.0. and Lean or LSS	5.66	5.75	5.52	5.65	5.69	5.84	5.56
Being able to use big data and dynamic data	5.91	5.84	6.00	5.98	5.69	5.79	5.97

Enablers	Sector			Type of Org.		Country	
	Overall	Manuf.	Service	LE	SME	Developing	Developed
Being trained in the use of I4.0. and Lean or LSS	5.66	5.72	5.57	5.70	5.54	5.84	5.56
Having integrated big data into statistical process control (SPC).	5.21	5.28	5.10	5.30	4.92	5.63	4.97
Having integrated I4.0. into the DMAIC problem-solving approach	5.02	5.16	4.81	5.15	4.62	5.58	4.71
Being able to collect, analyse and interpret big data in the measure and analyse phase of the DMAIC	5.23	5.41	4.95	5.35	4.85	5.68	4.97
Comprehensive understanding of data mining, data analysis and optimisation techniques with I4.0.	5.60	5.84	5.24	5.73	5.23	5.95	5.41
The dynamic involvement of stakeholders and continuous feedback through IoT	4.94	5.03	4.81	4.90	5.08	5.32	4.74
The integration of Big Data for determining the Voice of the Customer	5.15	5.16	5.14	5.28	4.77	5.74	4.82
Integration of I4.0. into the LSS toolkit	5.02	4.97	5.10	5.13	4.69	5.37	4.82
Understanding of I4.0. and Lean or LSS and their synergies	5.19	5.25	5.10	5.33	4.77	5.37	5.09
Involvement of stakeholders (i.e., customers and suppliers)	5.15	4.97	5.43	5.18	5.08	5.58	4.91

Overall: Overall mean scores, Manuf: mean scores in the manufacturing sector, service: mean score in the service sector, LE: mean scores in Large enterprises, SME: mean scores in small and medium scale enterprises, Developing: mean scores in developing countries Developed: mean scores in developed countries

Based on the analysis outcome delineated in Table 5, the top five enablers of LSS and I4.0 integration are: 1) Top management support, 2) being able to use big data and dynamic data, 3) multi-skilled or multi-talented personnel, 4) alignment of organisational strategies with I4.0, and Lean or LSS, and 5) being trained in using I4.0, and Lean or LSS. The result reveals that top management support was the most important enabler for I4.0 and LSS integration across the manufacturing and service sector, LE and SMEs, and developed and developing countries. Top Management support has been deemed an essential factor for both LSS (Antony, 2015; Antony *et* *al.*, 2018) and I4.0 implementation (Moeuf *et al.*, 2020; Sony and Naik, 2020). Thus, our study confirms that this is significant even in I4.0 and LSS integration. To test for differences across the sector, an independent sample Mann−Whitney *U* test was performed to test whether there is a significant difference between the manufacturing and service sectors. It was found that the difference is not significant (p>0.05). Similarly, there was no significant difference across LE and SMEs (p>0.05). However, there was a significant difference in the enablers' mean values between developing and developed countries. The following enablers differed 1) having integrated I4.0 into the DMAIC problem-solving approach (Developing country =5.58, Developed country = 4.71, p=0.044), 2) being able to collect, analyse and interpret big data in the measure and analyse phase of the DMAIC (Developing countries = 5.68, Developed countries = 4.97, p=0.048), and 3) the integration of Big Data for determining the Voice of the Customer (Developing countries = 5.74, Developed countries = 4.82 p=0.011). The findings of this study suggest that the integration of I4.0 technologies into the DMAIC problem-solving approach, as well as the ability to collect, analyse, and interpret big data in the measure and analyse phase of DMAIC, and the integration of Big Data for determining the voice of the customer, can lead to improved results in developing countries. These results may catalyse organisations in developing countries to adopt and integrate I4.0 technologies with LSS methodologies. The results indicate that developing countries may benefit more from integrating I4.0 technologies into the DMAIC problem-solving approach, with a higher mean score for this enabler than developed countries. This finding underscores the potential of I4.0 technologies to improve process efficiency, quality, and productivity in developing countries. Additionally, the study suggests that the ability to collect, analyse, and interpret big data in the measure and analyse phase of the DMAIC is significantly higher in developing countries, indicating a greater capability for utilising data-driven decision-making approaches. Moreover, the integration of big data for determining the voice of the customer was found to be more effective in developing countries, highlighting the potential for organisations to enhance customer satisfaction and loyalty.

4.2. Barriers

The barriers to LSS and I4.0 integration for the organisation was analysed, and the results are explicated in Table 6.

Table 6: Barriers to LSS and I4.0 Integration(Source: Author Constructed)

Barriers	Sector			Type of Org.		Country	
	Overall	**Manuf.**	**Service**	**LE**	**SME**	**Developed**	**Developing**
Difficulty in data collection	5.28	5.34	5.19	5.25	5.38	5.38	5.11
Poor understanding of data analysis (Cloud and Big Data)	5.70	5.69	5.71	5.65	5.85	5.71	5.68
Lack of prevention and resolution of problems through the use of AI technology without human interaction	5.33	5.48	5.10	5.49	4.85	5.09	5.78
Poor integration of I4.0. and Lean or LSS into the system design	5.14	4.93	5.43	5.13	5.17	5.18	5.06
Lack of security and data reliability	4.88	4.77	5.05	4.90	4.85	4.94	4.78
Lack of sustainable control and experiments	4.80	4.83	4.76	4.77	4.92	4.76	4.88
Poor distributed material and information flow	4.67	4.48	4.95	4.56	5.00	4.82	4.39
Lack of cultural transformation of the organisation in the use of I4.0. and Lean or LSS	5.27	5.13	5.48	5.23	5.38	5.41	5.00
Poor knowledge of optimisation and modelling of I4.0. and Lean or LSS	5.25	5.23	5.29	5.31	5.08	5.35	5.06
Poor ecosystem, infrastructure and investment to integrate I4.0. and Lean or LSS	5.37	5.47	5.24	5.46	5.08	5.26	5.59
Lack of real-time connectivity between the different processes of an organisation	5.21	5.19	5.24	5.18	5.31	5.21	5.22
Poor Intelligent monitoring	5.02	5.10	4.90	5.03	5.00	4.88	5.28
Lack of real-time visualisations and communications	5.20	5.27	5.10	5.21	5.17	5.12	5.35
Complete automation	4.59	4.57	4.62	4.61	4.54	4.56	4.65
Huge investments	4.96	5.27	4.52	5.00	4.83	4.76	5.35
Poor alignment with the strategy	5.40	5.42	5.38	5.33	5.62	5.32	5.56
Shopfloor resistance	4.80	4.83	4.76	4.68	5.15	4.76	4.89
Middle Management resistance	5.00	5.00	5.00	4.92	5.23	5.12	4.78
Lack of organisational strategies for technologies	5.08	5.00	5.19	4.97	5.38	4.97	5.28

Barriers	Sector			Type of Org.		Country	
	Overall	Manuf.	Service	LE	SME	Developed	Developing
Lack of framework/ roadmap for the deployment of I4.0. and Lean or LSS	5.25	5.42	5.00	5.41	4.77	5.06	5.61
Lack of assessing the risks when applying I4.0. with Lean or LSS on, for example, safety or employee well-being	5.02	5.10	4.90	5.13	4.69	4.76	5.50
Lack of knowledge of the methodologies and practices	5.29	5.39	5.14	5.31	5.23	5.29	5.28
Lack of top management support	5.63	5.65	5.62	5.51	6.00	5.68	5.56
Fear of work losing	5.12	5.32	4.81	5.13	5.08	4.85	5.61

According to the findings presented in Table 6, the foremost obstacles to integrating LSS and I4.0 are identified as follows. Firstly, there is a lack of adequate comprehension of data analysis, particularly in the Cloud and Big Data areas. Secondly, insufficient support from top management is perceived as a significant hurdle. Thirdly, there is a notable lack of alignment with the organisation's overall strategy. Fourthly, challenges are associated with the ecosystem, infrastructure, and investment necessary to integrate I4.0 and LSS. Lastly, effective problem prevention and resolution are absent through AI technology without human intervention. These findings suggest that a clear understanding of data analysis, particularly Cloud and Big Data, is essential to integrate LSS and I4.0 successfully. Moreover, top management support, alignment with the organisation's strategy, and investments in the necessary infrastructure and ecosystem are also critical factors. Additionally, using AI technology to address problems without human intervention can be a crucial enabler of successful integration. The Mann−Whitney *U* test was performed to test whether there is a significant difference between the manufacturing and service sector, and it was found that the difference is not significant ($p>0.05$). Similarly, there was no significant difference across LE and SMEs ($p>0.05$). Also, no difference was found concerning barriers between developed and developing countries ($p>0.05$). These findings emphasise the importance of addressing each barrier regardless of organisational type, location, or sector. All organisations must recognise and overcome these barriers to integrate LSS and I4.0 effectively. By doing so, organisations can leverage the benefits of these approaches and improve their operations and competitiveness in the marketplace.

4.3. Benefits

The main benefits of the LSS and I4.0 integration for the organisation are explicated in Table 7.

Table 7: Benefits of LSS and I4.0 integration(Source: Author Constructed)

Benefits	**Sector**			**Type of Org.**		**Country**	
	Overall	**Manuf.**	**Service**	**LE**	**SME**	**Developed**	**Developing**
Greater efficiency	5.94	6.03	5.81	5.98	5.85	5.97	5.89
Lowering operational costs	5.72	5.81	5.57	5.78	5.54	5.71	5.74
Reduction in WIP Inventory	5.38	5.53	5.14	5.35	5.46	5.18	5.74
Productivity improvement	5.72	5.84	5.52	5.70	5.77	5.59	5.95
Increase in overall equipment effectiveness (OEE)	5.60	5.91	5.14	5.58	5.69	5.53	5.74
Increased customer satisfaction	5.69	5.68	5.71	5.87	5.15	5.56	5.94
Energy usage reduction rendered increased significantly over the LSS application	5.39	5.57	5.14	5.50	5.08	5.33	5.50
Reduction in rejection rate	5.53	5.77	5.19	5.53	5.54	5.36	5.83
Reduction in cost-of-service delivery	5.37	5.40	5.33	5.29	5.62	5.39	5.33
Reduction in manufacturing lead time	5.53	5.73	5.24	5.42	5.85	5.45	5.67
Reduction in defects	5.67	5.97	5.24	5.68	5.62	5.58	5.83
Increase in business reputation and scope of new business generation	5.39	5.57	5.14	5.55	4.92	5.39	5.39
Improve the quality of service	5.67	5.70	5.62	5.74	5.46	5.55	5.89
Increased throughput	5.43	5.70	5.05	5.42	5.46	5.33	5.61
More Leadership engagement	4.92	5.10	4.67	4.95	4.83	4.70	5.35
Better quality performance	5.69	5.73	5.62	5.71	5.62	5.64	5.78
Higher customer satisfaction	5.63	5.57	5.71	5.68	5.46	5.42	6.00
Better business performance	5.68	5.86	5.43	5.76	5.46	5.67	5.71
Greater Asset Utilisation	5.55	5.67	5.38	5.66	5.23	5.52	5.61
Improved after-sales services	5.06	5.07	5.05	5.00	5.23	4.94	5.28

Based on the outcome provided in Table 7, the top five main results of the integration of LSS and I4.0 are 1) Greater efficiency, 2) Lowering operational costs, 3) Productivity improvement, 4) Increased customer satisfaction, and 5) Better quality performance. Previous studies have depicted that I4.0 implementation in the organisation has resulted in greater efficiency, reduced cost, improved productivity, increased customer satisfaction and improved performance (Arromba *et* *al.*, 2020; Kiel *et al.*, 2017; Sony, Antony, Mc Dermott, *et al.*, 2021). The integration of LSS and I4.0 is also hypothesised to achieve new levels of optimum performance in terms of efficiency, costs, productivity, customer satisfaction and quality performance, irrespective of the nature of the organisation, sector, and type of economy (Macias-Aguayo et al., 2022; Vinodh et al., 2021). The study empirically examines the claim about the benefits of LSS and I4.0 integration and finds that the integration of LSS and I4.0 is a powerful combination that significantly benefits organisations. Greater efficiency, lower operational costs, productivity improvement, increased customer satisfaction, and better quality performance are the top five benefits that organisations can expect.

Further, the Mann−Whitney *U* test was performed to test whether there is a significant difference between the manufacturing and service sector. It was found that the difference is significant in benefits as there is 1) an increase in overall equipment effectiveness (OEE) ($p=0.047$), 2) reduction in defects ($p =0.036$). Thus, an improvement in OEE and reduction in defects were higher in manufacturing compared to services but OEE and defect reduction are well-defined concepts in manufacturing. Hence, the integration has brought marked improvements in manufacturing compared to services. In terms of differences in LE and SMEs, no significant difference was noted, suggesting the equal nature of benefits. In terms of developing and developed countries, it was found that the reduction in WIP Inventory ($p= 0.041$) differed across developing and developed countries. The production systems in developing countries are more volatile, uncertain, and ambiguous than in developed countries (Luthra *et al.*, 2020; Sharif and Irani, 2017). These countries are more susceptible to disruption, labour intensive, old technologies, non-specialised labour, social, political and other factors (Guasch and Kogan, 2001; da Silva *et al.*, 2016). Thus, LSS and I4.0 integration brings marked improvement in work in progress (WIP) in developed countries as compared to developing countries.

4.4. I4.0 technologies integration in DMAIC phases

The study further investigated which I4.0 technologies can be integrated and effectively used within the DMAIC phases during Six Sigma integration. The most influential technologies based on frequency in each phase of Six Sigma are explicated in Table 8.

Table 8: LSS and I4.0 integration in DMAIC phases(Source: Author Constructed)

I4.0 Technologies	Define	Measure	Analyse	Improve	Control
Not listed I4.0 Technologies*	15	25	24	34	28
Additive Manufacturing	4	10	13	30	16
Augmented Reality	8	12	23	33	14
Autonomous Robots	5	12	14	36	21
Big Data Analytics	14	31	40	22	24
The Cloud	10	14	17	19	19
Cybersecurity	9	10	11	21	25
Blockchain	12	12	13	28	23
The Industrial Internet of Things	9	17	21	33	26
Simulation	8	22	33	34	15
Artificial Intelligence	13	25	35	33	25
Automation	6	19	18	37	30
The values in the table are frequency. *Not listed technologies are those not listed in the survey (Big Data and Analytics, Artificial Intelligence, I4.0 Technologies, Simulation, Automation, The Industrial Internet of Things, Augmented Reality, Autonomous Robots, Blockchain, The Cloud, Cybersecurity, Additive Manufacturing					

Based on the analysis of findings provided in Table 8, the top 3 most frequently applied technologies in each phase of Six Sigma are depicted in Table 9.

Table 9: LSS and I4.0 technologies(Source: Author Constructed)

Phases of Six Sigma	First Position	Second Position	Third
Define	Not listed I4.0 Technologies*	Big Data Analytics	Artificial Intelligence
Measure	Big Data Analytics	Not listed I4.0 Technologies	Artificial Intelligence
Analyse	Big Data Analytics	Artificial Intelligence	Simulation

Improve	Automation	Autonomous Robots	Not listed I4.0 Technologies
Control	Automation	Not listed I4.0 Technologies	The Industrial Internet of Things
*Not listed technologies are those not listed in the survey (Big Data and Analytics, Artificial Intelligence, I4.0 Technologies, Simulation, Automation, The Industrial Internet of Things, Augmented Reality, Autonomous Robots, Blockchain, The Cloud, Cybersecurity, Additive Manufacturing			

The present study elucidates that in the initial Define phase of the LSS and I4.0 integration process, it is imperative to incorporate various I4.0 technologies besides big data analytics and artificial intelligence. However, it should be noted that organisations must prioritise context-specific technologies during the integration process, and there is no dominant I4.0 technology for this phase. Big data analytics is the most crucial I4.0 technology in the subsequent Measure and Analyse phase. Finally, in the Improvement and Control phase, automation represents a significant I4.0 technology that necessitates consideration in the integration process. This result depicts the importance of incorporating I4.0 technologies into the LSS methodology at different stages of the integration process. The Define phase, the initial stage, is critical for the integration process. To achieve successful integration, it is essential to consider various I4.0 technologies beyond big data analytics and artificial intelligence. This emphasises the importance of selecting context-specific technologies that align with the organisation's unique needs. Big data analytics is highlighted as the essential I4.0 technology in the subsequent Measure and Analyse phase. This is because big data analytics facilitates the extraction of valuable insights from large datasets to identify areas for improvement. The insights obtained from big data analytics can inform decisions and drive the optimisation of processes, thereby increasing the efficiency and effectiveness of the organisation. Finally, the Improve and Control phase emphasises the importance of automation as a significant I4.0 technology to consider. Automation can reduce the potential for human error and enhance the consistency and reliability of processes. Organisations can increase efficiency, reduce costs, and improve quality by automating tasks, achieving optimal performance. Figure 1 depicts the use of various I4.0 technologies across all the phases of DMAIC. The number value in the figure indicates the frequency.

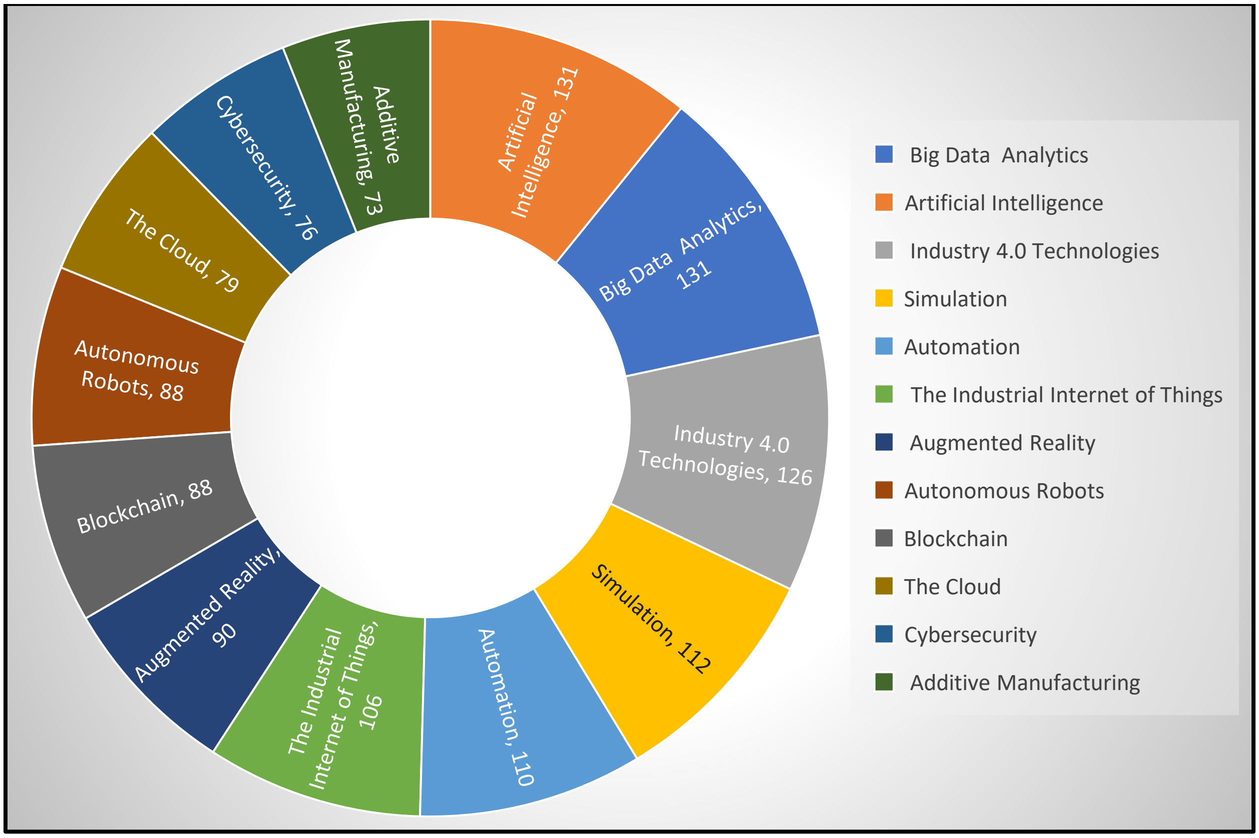

Figure 1: I4.0 technologies across all the phases of DMAIC(Source: Author Constructed)

Integrating I4.0 technologies with LSS methodology can enhance the efficiency and effectiveness of organisations. However, to achieve successful integration, it is essential to identify the leading technologies that can facilitate the integration process across all the phases of the DMAIC methodology. Based on the current research, the top five technologies for LSS and I4.0 integration across all the phases of DMAIC are as follows:

- Big Data Analytics: This technology enables organisations to extract valuable insights from large datasets to identify areas for improvement, thereby facilitating the integration process across all the phases of DMAIC(Alalawneh and Alkhatib, 2021; Azeem *et al.*, 2022).
- Artificial Intelligence: This technology enhances the automation of tasks and can improve decision-making processes by providing valuable insights and predictions based on data analysis(Liu *et al.*, 2020; Sharma *et al.*, 2022).
- Other I4.0 technologies: Besides big data analytics and artificial intelligence, other I4.0 technologies, such as digital twins, can facilitate the integration process across all DMAIC

phases by improving data collection, enhancing communication, and providing real-time monitoring and feedback(Chen and Huang, 2020).

- Simulation: This technology allows organisations to test different scenarios and analyse their potential impact before implementation, thereby reducing the risk of failure and optimising processes (Bhat *et al.*, 2020). This technology can enhance the consistency and reliability of processes, reduce the potential for human error, and increase efficiency by automating tasks (Automation, 2014; Bessen *et al.*, 2020; Frohm *et al.*, 2008).

5. Theoretical Implications

The empirical analysis presented in this study makes a valuable academic contribution to operations management by providing insights into integrating LSS and I4.0 technologies. There is no empirical study yet on LSS and I4.0 integration. However, the study sheds light on the key enablers, barriers, benefits, and technologies that influence the integration of LSS and I4.0 in organisations. One of this study's key contributions is identifying top management support as the most significant enabler for integrating LSS and I4.0. This finding is significant because it highlights the critical role that senior leaders play in driving organisational change and transformation. Another significant contribution of this study is identifying a poor understanding of data analysis as the most crucial barrier to integrating LSS and I4.0. This finding highlights the importance of investing in employee training and development to build the necessary skills and competencies for data analysis and interpretation. The study emphasises the need for organisations to provide ongoing training and support for employees to enhance their data literacy and analytical capabilities. Another valuable academic contribution is the study's identification of the benefits of integrating LSS and I4.0, such as increased efficiency, lower operational costs, productivity improvement, increased customer satisfaction, and better-quality performance. This finding provides empirical evidence of the tangible benefits organisations can achieve by integrating LSS and I4.

6. Managerial Implications

Organisations can use this study to understand the enablers they must consider before implementing LSS and I4.0 integration. Secondly, organisations can understand the benefits and barriers while integrating LSS and I4.0. This study details the benefits and barriers based on sector, type of organisation and nature of the economy, thus helping organisations implement successfully. Finally, this study can be used as a guideline regarding which I4.0 technologies are in different phases of LSS. From a practical perspective, managers can use the findings of this study to integrate LSS and I4.0 in their organisations effectively. They can start by ensuring top management support for the integration effort, which is the most significant enabler.

Additionally, they can focus on improving employees' understanding of data analysis to overcome the crucial barrier identified in the study. By doing so, managers can expect multiple benefits, such as increased efficiency, lower operational costs, productivity improvement, increased customer satisfaction, and better-quality performance. Managers should also consider the critical role of I4.0 technologies, particularly Big Data Analytics and Artificial Intelligence, in different phases of LSS. They can invest in these technologies to optimise the integration of LSS and I4.0, especially during the DMAIC phase. Finally, managers should adopt a strategic approach to technology adoption and implementation to ensure successful integration.

7. Conclusion, limitations, and direction for future research

This empirical analysis sheds light on the crucial factors affecting the integration of LSS and I4.0, including enablers, barriers, benefits, and technologies. The study highlights the importance of top management support as the most significant enabler and a poor understanding of data analysis as the most crucial barrier. By integrating LSS and I4.0, organisations can achieve multiple benefits, such as increased efficiency, lower operational costs, productivity improvement, increased customer satisfaction, and better-quality performance. Finally, the study emphasises the critical role of I4.0 technologies, particularly Big Data Analytics and Artificial Intelligence, in different phases of LSS, especially DMAIC. This study provides valuable insights for organisations seeking to integrate LSS and I4.0 effectively, enabling them to stay ahead in a highly competitive environment.

One of the limitations of this study is the sample size. LSS and I4.0 are emerging concepts (Antony *et al.*, 2022) hence obtaining a larger sample size is difficult. Instead, a pilot study was used to understand the enablers, benefits, barriers, and technologies in LSS and I4.0 integration. However, future studies should be devoted to understanding the LSS and I4.0 integration from a country perspective. Another area would be to conduct a longitudinal case study to understand how the temporal variation would be experienced in benefits and drivers while implementing LSS and I4.0.

Organisational culture plays a significant role in successfully implementing LSS (Knapp, 2015). Therefore, future studies should investigate the impact of organisational culture on integrating I4.0 and LSS. Additionally, it was impossible to list all I4.0 technologies in the survey to investigate their impact on different phases of LSS. Therefore, future studies should explore other I4.0 technologies, apart from those already mentioned, such as Big Data Analytics, Artificial Intelligence, I4.0 Technologies, Simulation, Automation, The Industrial Internet of Things, Augmented Reality, Autonomous Robots, Blockchain, The Cloud, Cybersecurity, and Additive Manufacturing, on each phase of the DMAIC methodology. Another prospective area for research would be how I4.0 technologies can be integrated into different phases of Design for Lean Six Sigma.

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