Tomas Bata University in Zlín
Faculty of Management and Economics

Doctoral Thesis

# Integration of the Lean Six Sigma methodology within the Industry 4.0 framework

## Integrace metodiky Lean Six Sigma v rámci Průmyslu 4.0

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# ABSTRACT

The technological changes happening in the industrial world have an impact on every aspect of industrial life. In 2011, this change was called Industry 4.0 or the $4^{th}$ Industrial Revolution. In the context of the Industrial Revolution, the understanding of the production process needs to be changed according to the environment to be able to respond to the requirements of the market with a more personalized proposition. Thus, Industry 4.0 influences every aspect of industrial life, including technological, managerial, and human.

As the change is unavoidably connected with manufacturing, the understanding of the change might benefit companies' management from the point of view of better understanding the processes and facilitating a smoother shift towards the requirements of the contemporary environment. Both practitioners and scientists have begun to think about the existing managerial approaches to adapt them to the advanced industrial world.

One of the methodologies that has proved its successful influence on manufacturing processes in the $20^{th}$ and $21^{st}$ centuries is Lean Six Sigma (LSS). Emerging from 2 separate approaches – Lean and Six Sigma – LSS has combined the best practices of both and allowed companies' management to improve processes by leveraging both statistical methods and creative thinking aimed at waste and variance reduction.

In this research, an attempt is made to understand the influence of Industry 4.0 on the success of Lean Six Sigma projects in the industrial world. The main objective is to analyze the Integration of Lean Six Sigma methodology within the Industry 4.0 framework.

To achieve this goal, a combination of qualitative and quantitative research is implemented to analyze the preliminary data gathered from companies involved in the industry. The data will be used to assess the extent to which Industry 4.0 technologies influence LSS projects' success and to determine if the implementation of Industry 4.0 technologies is correlated with LSS projects' success more than a company's characteristics (as company's size, company's industry, company's experience in LSS, certification in LSS, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology,

active trainings on LSS, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory) or project characteristics (Such as project budget, project duration, number of project's participants). Moreover, an attempt is made to identify the key Industry 4.0 technologies used in LSS projects and the LSS tasks that the Industry 4.0 technologies help to deal with.

The study concludes that the future of Lean Six Sigma methodology within the scope of the Industry 4.0 era holds great potential and that the convergence of Lean Six Sigma and Industry 4.0 is a mutually beneficial connection.

This research could be of interest to researchers to assess the mutually beneficial conjunction between LSS and Industry 4.0. It would also be helpful for industrial managers to consider output when establishing more efficient production processes, introducing new technologies into existing processes, and improving LSS projects.

# ABSTRAKT

Technologické změny v průmyslovém světě mají dopad na všechny aspekty průmyslového života. V roce 2011 byla tato změna nazvána Průmysl 4.0 nebo čtvrtá průmyslová revoluce. V kontextu průmyslové revoluce se musí chápání výrobního procesu změnit v závislosti na prostředí, aby bylo možné reagovat na požadavky trhu personalizovanější nabídkou. Průmysl 4.0 tak ovlivňuje všechny aspekty průmyslového života, včetně technologických, manažerských a lidských.

Jelikož je tato změna nevyhnutelně spojena s výrobou, mohlo by její pochopení být pro management podniků přínosem z hlediska porozumění procesům a usnadnění hladšího přechodu k požadavkům současného prostředí. Odborníci z praxe i vědci se začali zabývat stávajícími manažerskými přístupy s cílem přizpůsobit je pokročilému průmyslovému světu.

Jednou z metodik, která prokázala svůj úspěšný vliv na výrobní procesy ve 20. a 21. století, je Lean Six Sigma (LSS). Vznikla ze dvou samostatných přístupů – Lean a Six Sigma – LSS spojila nejlepší postupy obou a umožnila managementu firem zlepšovat procesy na základě statistického faktoru i kreativního myšlení.

V tomto výzkumu je učiněn pokus o pochopení vlivu Průmyslu 4.0 na metodiku Lean Six Sigma v průmyslovém světě. Hlavním cílem tohoto výzkumu je analyzovat Integrace metodiky Lean Six Sigma v rámci Průmyslu 4.0.

K dosažení tohoto cíle je implementována kombinace kvalitativního a kvantitativního výzkumu, který analyzuje data předběžně shromážděná od průmyslových firem. Tato data budou využita k posouzení míry, do jaké technologie Průmyslu 4.0 ovlivňují úspěšnost projektů LSS, a ke zjištění, zda implementace technologií Průmyslu 4.0 koreluje s úspěšností projektů LSS více než charakteristiky společnosti (jako je velikost společnosti, odvětví, zkušenosti s LSS, certifikace v LSS, zkušenosti s Průmyslem 4.0, aktivní využívání přístupu Kaizen a metodiky Lean Six Sigma, aktivní školení v LSS, aktivní zavádění technologií Průmyslu 4.0 a snaha o vytvoření Smart factory) nebo charakteristiky projektu (jako je rozpočet projektu, délka trvání projektu a počet účastníků projektu). Dále je vyvinuta snaha identifikovat klíčové technologie Průmyslu 4.0 využívané v projektech LSS a úkoly v rámci LSS, které tyto technologie pomáhají řešit.

Závěr studie prokazuje že budoucnost metodologie Lean Six Sigma v rámci éry Průmyslu 4.0 má velký potenciál a že spojení Lean Six Sigma a Průmyslu 4.0 je vzájemně prospěšným spojením.

Tento výzkum by mohl být zajímavý pro výzkumné pracovníky za účelem posouzení vzájemně prospěšného propojení mezi LSS a Průmyslem 4.0. Pro průmyslové manažery by pak mohly být jeho výstupy užitečné při zvažování zavádění efektivnějších výrobních procesů, implementaci nových technologií do stávajících procesů a zdokonalování projektů LSS.

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LSS – Lean Six Sigma

I4.0 – Industry 4.0

PM – Project Management

CPS – Cyber Physical System

QM – Quality Management

BDA – Big Data Analytics

AI – Artificial Intelligence

I5.0 – Industry 5.0

# 1. INTRODUCTION

## 1.1. Research background and research problem

The contemporary technological advancement and increasing complexity have significantly influenced both industrial and non-industrial environments. This has led to a situation in which all the processes and practices existing in the world should be modified accordingly. Today, the quote “here we must run as fast as we can, just to stay in place. And if you wish to go anywhere you must run twice as fast as that” written by Lewis Carroll for Alice in Wonderland does not seem like a fairy-tale quote, but as a real fact. Moreover, this became a characteristic feature of the industrial reality that should not only increase the speed of processes but also improve the proposition answering the increasing amount of diverse customer demand (Mayr, et al., 2018). Thus, the quality of the product receives even greater attention from quality managers (Dogan & Gurcan, 2018). Otherwise, the situation does not seem plausible for production and specifically for industrial competition with the expanding globalization and the rising speed (Rauch, Dallasega, & Matt, 2016), (Uriarte, Ng, & Moris, 2018).

These changes in technologies pushed the scientific and practical communities to reflect on the possibilities of shifting existing processes towards the creation of digitalized conditions for industrial and social life, thereby addressing the existing requirements. Several frameworks and models have already been developed to manage the challenge and shift the principles toward creating “smart processes.” (Leyh, Martin, & Schaeffer, 2017), (Rauch, Dallasega, & Matt, 2016). Even though the integration of these principles is inextricably connected to new opportunities, challenges are also an essential part of it.

Products nowadays are “becoming ‘smart’” (Rauch, Dallasega, & Matt, 2016). This provides an impulse towards faster development and the formation of a new industrial environment known as Industry 4.0. These digitalized changes are directed to the creation of a “smart factory” where all the processes will be interconnected and interrelated (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019). The creation of such an industrial model includes the adjustment of different managerial and industrial practices. One of these existing practices that has proved to be successful in many companies is Lean Six Sigma.

Several authors have already proposed the framework for Lean and Industry 4.0 conjunction and noted that the principles of Lean should be evaluated in the scope of Industry 4.0 (Leyh, Martin, & Schaeffer, 2017), (Sony, Industry 4.0 and lean management, 2017), (Rosin, Forget, Lamouri, & Pellerin, 2020), (Bhat, Bhat, & Gijo, 2020). Moreover, Lean principles are often considered to be able to provide a good basis for Industry 4.0 implementation, but the number of studies is currently not sufficient (Leyh, Martin, & Schaeffer, 2017), (Rossini, Costa, Staudacher, & Tortorella, 2019a). The conjunction of Lean and Industry 4.0 is interesting from both sides – from the point of view of implementing Lean into the framework of the introduction of Industry 4.0, and from the point of view of the influence of Industry 4.0 technologies on Lean tools (Leyh, Martin, & Schaeffer, 2017), (Rauch, Dallasega, & Matt, 2016).

Several attempts were also made to combine Lean and Six Sigma tools with separate Industry 4.0 technologies. In the majority of cases, these combinations proved to be effective (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019), (Ahmed, Page, & Olsen, 2020), (Celano, Costa, Fichera, & Tringali, 2012), (Dogan & Gurcan, 2018), (Gupta, Modgil, & Gunasekaran, 2020), however, some authors doubt the suitability of these tools for complex processes typical of the Industry 4.0 environment (Uriarte, Ng, & Moris, 2018), and claim that further studies are necessary to assess this aspect better.

From the point of view of Lean Six Sigma as a methodology, the influence of Industry 4.0 on it has hardly been evaluated (only 62 published articles as of the end of the year 2024), as well as the analysis of the required Industry 4.0 technologies for LSS projects' success. The importance of the topic can also be proven by the comprehensive bibliometric analysis, that confirms that integrating LSS with Industry 4.0 requires a thorough understanding of both and underlines the need for future research with the focus on developing models that address the complexities of combining process improvement techniques with advanced digital technologies, thus, paving the way for future advancements in both academic and practical applications (Citybabu & Yamini, 2023), (Tissir et al., 2024), (Skalli et al., 2024)). In their work, Yadav N., Shankar R., and Singh S.P. (2020a) directly state the question of the influence of Industry 4.0, Quality 4.0, and Lean Six Sigma on one another. The need for more empirical studies, while advocating for further exploration into how LSS can complement Industry 4.0 adoption for operational excellence, was also stated by Skalli et al. (Skalli et al., 2023a). Moreover, there was no information found on the requirements of the company’s size, the company’s experience in LSS, certification in LSS, belt types presented in the company, project duration, or experience in Industry 4.0 for LSS project success in the Industry 4.0 era. At the same time, the importance of the change in this field was mentioned by the authors, dealing with the topic, and the necessity of a deeper understanding of the combination of Lean Six Sigma and Industry 4.0 was noted.

Due to the pressure of the introduction of new technologies into robust processes, it’s paramount that the influence of Industry 4.0 is examined in the context of its influence on the LSS projects’ success. Thus, this work aims to assess whether Industry 4.0 technologies correlate with LSS projects’ success based on the data gathered in industrial companies and to seek the optimized approach for their integration. The examination of the variables will be based on the extent to which the independent Industry 4.0 technologies predict each of the dependent LSS project’s outcome variables (budget, schedule, and effectivity).

## 1.2 Research Questions and Hypothesis

Based on the research gaps, the research problem that was identified is a *need to better understand LSS in the Industry 4.0 era from the point of view of its integration and mutual influence.* Thus, the main research goal is *to determine the influence of Industry 4.0 on LSS projects*.

Following the research goal, the research questions that contribute to the existing literature gap are mentioned below.

Main Research question:

*How do the Industry 4.0 technologies and company culture in manufacturing companies influence the Lean Six Sigma projects and contribute to project success?*

Constituent research questions:

1. What are the Industry 4.0 technologies that are used in SME and large companies in the Czech Republic for LSS projects?
2. What are the barriers to the introduction of Industry 4.0 technologies in the Czech Republic?
3. Is LSS and Industry 4.0 a beneficial conjunction?

The objective is to verify the proposition that Industry 4.0 has a positive influence on LSS projects and assess the challenges emerging from the conjunction.

4. What is the association between LSS project success (from the point of view of time, budget and efficiency) and company's characteristics, such as company's size, company's industry, company's experience in LSS, certification in LSS, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology, active trainings on LSS, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory?

The objective is to identify if the LSS project success could be defined by the company's characteristics, such as company's size, company's industry, company's experience in LSS, certification in LSS, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology, active trainings on LSS, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory.

5. What is the association between LSS project success (from the point of view of time, budget, and efficiency) and project characteristics such as project duration, number of project participants, and project budget?

The objective is to understand if the LSS project's success can be influenced by the project's characteristics, such as project duration, number of project participants, and project budget.

6. To what extent is the utilization (usage) of Industry 4.0 technologies related to the LSS project success outcome?

The objective is to contribute to the understanding of the influence of Industry 4.0 technologies on the success of LSS projects.

## 1.3 Significance of the research

In the current industrial landscape, many companies are struggling to optimize processes, reduce operational costs, and maximize profitability to be able to maintain a competitive advantage. As the development of advanced technologies is happening faster than the adaptive capacity of many industrial companies, it becomes crucial to determine how different methodologies should be optimized to respond to the existing industrial environment. Therefore, this study is essential, as it offers a results-oriented analysis to better understand Lean Six Sigma methodology in the Industry 4.0 era.

The research also helps to identify necessary adaptations of the Lean Six Sigma methodology to ensure project success. At the same time, it evaluates the extent to which companies' characteristics could influence the change towards the new development. Simultaneously, this dissertation fills a significant gap between theoretical claims of synergy between Lean Six Sigma methodology and the Industry 4.0 concept and the divergence between perceived potential and actual performance.

Finally, the study provides a practical strategic framework that would guide researchers and practitioners in the ever-changing industrial world on how to implement or ameliorate the combination of Lean Six Sigma methodology with Industry 4.0 technologies to achieve project success.

# 2. THEORETICAL FRAMEWORK

This part of the dissertation establishes the theoretical background of the topic by examining the historical evolution and current state of the key notions that are Industry 4.0, Lean Six Sigma, and its constituents. The primary objective of this part is to clarify key notions to avoid ambiguity and ensure conceptual clarity, and to summarize the current state of the literature.

## 2.1 Industry 4.0

The term Industry 4.0 was proposed by the German Government at the Hannover fair in 2013 (Salkin, Oner, Ustundag, & Cevikcan, 2018), (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019) as an attempt to describe the augmented digitalization in everyday life. Nowadays, more than a decade later, the understanding of this term, however, has some common aspects in the majority of works, which could slightly vary from the pure understanding of the Industrial Internet (Leyh, Martin, & Schaeffer, 2017), to the creation of a smart factory (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019), and a simple mixture of advanced technologies (Pereira, Dinis-Carvalho, Alves, & Arezes, 2019), which are typical for this topic. The general understanding of Industry 4.0 always includes the transition towards flexible, interconnected, and self-controlled principles (Leyh, Martin, & Schaeffer, 2017), that connect physical and virtual systems.

Industry 4.0 is presented as the Fourth Industrial Revolution and is seen as the next step in industrial and technological development. However, the fact of the new industrial revolution is not mutual for all the authors, and some doubt that industrialization is a real step, as it does not create anything new from the economic and technological point of view (Евстафьев, 2012-2021). However, the fact that the environment is changing is undeniable.

The previous industrial revolutions were connected with other industrial changes that greatly affected the community. Thus, the first industrial revolution is connected with the invention of the steam engine and the first mass production. This has led to great changes in industrial life, i.e., the creation of steam motors provided the major impulse for the creation of transportation technologies, namely the railroad development that allowed production to be transported. The second industrial revolution was due to energy and chemistry technology advancement, and steel production. This moved the technologies to the next level and allowed the creation of the first automobile, telephone, and telegraph. The third industrial revolution is seen as the appearance of communication systems and nuclear energy, which are still influencing our lives, and the advancement of which led to the fourth industrial revolution. In the fourth industrial revolution, the improvements are provided by the development of Internet technologies, allowing better data storage and processing, Cyber and artificial intelligence concepts, and automatic communication. "The fourth industrial revolution is a new level of organization of production and creation of high-tech products" (Ustinova, 2018).

The growing individualized demand, product advancement, and increasing interest towards the efficient usage of resources introduce the need to coordinate and connect actions and information for industries (Salkin, Oner, Ustundag, & Cevikcan, 2018). This gives momentum to the development of technologies that will be able to communicate and make simple decisions. The systems should be able to self-control and maintain good working conditions.

Industry 4.0 is usually associated with several new technologies that allow production to undergo major changes. The set of these technologies may vary depending on the source, but the majority of authors include the key elements that are adaptive robotics, big data analytics (BDA), simulation, cyber-physical systems, industrial Internet, cloud systems, additive manufacture (Salkin, Oner, Ustundag, & Cevikcan, 2018), (Chromjaková, Tuček, & Bobák, 2017), (Sony, Industry 4.0 and lean management, 2017), (Pereira & Romero, 2017), (Uriarte, Ng, & Moris, 2018), (Sordan, Oprime, Pimenta, Silva, & González, 2021). Adaptive robotics deals with adaptive robots that could provide easier production (Salkin, Oner, Ustundag, & Cevikcan, 2018). Big Data is connected with the work with information and the ever-growing amount of data and its processing (Salkin, Oner, Ustundag, & Cevikcan, 2018). Simulation allows the creation of a 3D model of production flow with key parameters (Chromjaková, Tuček, & Bobák, 2017) and to implement the testing of the system before its application. Cyber-Physical Systems establish a correlation between the physical world and computation (Salkin, Oner, Ustundag, & Cevikcan, 2018), with the purpose of creating agile production (Sony, 2017). The organizations with Cyber-Physical systems are called smart factories (Sony, 2017). The Industrial Internet of Things creates a network for these smart factories (Sony, 2017), and allows the physical process to be connected with virtual reality (Chromjaková, Tuček, & Bobák, 2017) and to share data (Kale, Katke, Dayane, & Thakar, 2022). As all these processes are connected with data, the flexible data storage available in real-time is called Cloud systems (Efimova, Briš, & Efimov, 2021). Additive manufacturing empowers the production of objects from digital models using varied materials.

The Industry 4.0 concept aims to create an environment where independence and flexibility exist at all levels (Leyh, Martin, & Schaeffer, 2017). This includes both production and managerial parts, and the way they are interconnected. The idea is to create interconnected and self-maintaining processes that would be able to work independently. Considering the ever-growing complexity and increasing customer needs, Industry 4.0 has huge potential (Pereira, Dinis-Carvalho, Alves, & Arezes, 2019) and it could help organizations to stay on the market.

## 2.2 Lean Six Sigma

Lean Six Sigma, as a methodology, has appeared in conjunction with two separate methodologies, Six Sigma and Lean. The basic idea of the methodology is to give “the concepts, methods, and tools” to improve the processes (Snee, 2010).

Both methodologies proved their efficiency in optimization process practices and cost reduction in many different companies. The difference between methodologies is that Lean considers that the source of waste is non-value-added activities, while Six Sigma defines the major source as variation (Dogan & Gurcan, 2018). Thus, Lean concentrates on the speed of the process, and Six Sigma on Accuracy (Abu Bakar, Subari, & Mohd Daril, 2015). Lean Six Sigma is connected with the third production system, as the first two were manual work and mass production (Leyh, Martin, & Schaeffer, 2017).

As the term is a conjunction of two separate practices, Lean and Six Sigma, there is a need to look deeper at each of the constituents to better understand the details of the approach.

### 2.2.1 Lean methodology

When the interest in TQM started to decrease, the interest in Kaizen provided growing concern towards Lean (Balzer, Francis, Krehbiel, & Shea, 2016). Lean has received attention as Toyota could make an increasing income even during some complicated economic periods (Pereira, Dinis-Carvalho, Alves, & Arezes, 2019).

Lean as a term has evolved in the 1990s following the concepts developed by Taiichi Ohno for the Toyota Production System. The term “Lean” became widespread with the book “The Machine That Changed the World: The Story of Lean Production” by James P. Womack et al. (Womack, Jones, & Roos, 2011). The basic principle of the Lean system is to eliminate seven kinds of waste, thus creating a more effective production system.

“Lean management thinking is used to differentiate between waste and value within an organization.” (Sony, 2017). In Lean, the waste (also called “muda”) is connected with activities that take time without adding value to the product. “Anything in production that does not add value is considered to be a form of waste.” (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019). There are seven waste types accepted in the world:

- overproduction – an enterprise produces extra without need,
- waiting – delays and idle time when the product is waiting to be finished,
- transportation – materials or products are moved when they are no longer required,
- over-processing – produce anything that the customer is not demanding, the product has,
- inventory – unnecessary storage of materials, products, and non-finished items,
- unnecessary motion – the movement of personnel that could be avoided,
- defects – defective items or items of unsatisfactory quality (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019).

Contemporary, the eighth form of waste becomes more frequent – it is non-utilized talent (Gay, 2018). This form of waste is connected with people and their adequate training, so that the company can benefit from their talents. This form of waste has inspired many companies to change their policies towards personal development. The reduction of the kinds of waste mentioned above has proved to be useful for improving companies' profits.

Existing for several decades, Lean has proved to be a successful system for many companies. Companies that want to meet market requirements with less waste benefit from the usage of Lean tools (Satoglu, Ustundag, Cevikcan, & Durmusoglu, 2018). The goal of Lean is to develop a "smooth flow of processes" (Antony, Gupta, Sunder M., & Gijo, 2018) in order to increase the effectiveness of production and achieve organizational goals. To achieve these goals, special tools and techniques are used (Glukhov & Kolobov, 2019). The most used tools are Value Stream Mapping, Lean Office, Lean Metrics, Push and Pull, Kaizen, 5S, SMED, Jidoka, Total Product Maintenance, and others (Sony, 2017).

The application of Lean principles and adoption of Lean Production received close attention and moved from being a one-company strategy to a whole world practice. Thus, Lean has proved its importance and has taken a significant part in improving processes and increasing profits.

### 2.2.2 Six Sigma

Six Sigma first appeared in the Motorola company in 1980 (Adams, Gupta, & Wilson, 2003) and was further enhanced in GE by the introduction of DMADV (Polk, 2011) and further development of the approach to the R&D stage called Design for Six Sigma (Snee, 2010).

The main principle of Six Sigma is to control variability and decrease defects. The process optimization is data-driven with key concepts of Critical-to-quality, Defect, Process Capability, Variation, and Stable operation (Mahanti & Antony, 2005). The amount of defects that are considered to be reasonable in Six Sigma is 3.4 per million opportunities; thus, the quality level in Six Sigma is 99.99966% (Zhevnov, 2013), as the term Six Sigma corresponds to six standard deviations (Sekhar & Mahanti, 2006), (McCarthy & Stauffer, 2001).

Six Sigma is a methodology with a strong statistical and data-gathering base. The data is usually processed following a structured circle – either DMAIC or DFSS:

- DMAIC is usually used when incremental change is necessary. Each letter stands for the step in the cycle: Define, Measure, Analyze, Improve, and Control. The CTQ parameters are usually defined at the initial stage and are further analyzed with the use of corresponding tools: ANOVA, Pareto analysis, SIPOC, t-tests, FMEA, and others. Then the ideas to improve the situation are generated, and the new process is controlled.

- DFSS is a shortening for Design for Six Sigma. This method is used for new processes and helps to identify defects at the early stages of production (Ramakrishnan, Tsai, Drayer, & Srihari, 2008). Several cycle variations are used in the scopes of DFSS – DMADV (Define, Measure, Analyze, Design, Verify), IDOV (Identify, Design, Optimize, Validate), DIDES (Define, Initiate, Design, Execute, Sustain), IIDOV (Invent, Innovate, Develop, Optimize, Verify), and others (Shahin, 2008).

Another peculiarity of Six Sigma is its strong organizational culture with a belt system. There are Yellow, Green, Black, and Master Black Belts, Champions, and Sponsors:

- Yellow Belts are team members with only a basic understanding of Six Sigma principles, and they are usually involved in the project to some extent.
- Green belts usually undergo a couple of weeks of training on Six Sigma, and they understand both Six Sigma principles and processes that need to be improved (George, 2002).
- Black belts are team members who have experience with Six Sigma projects and extensive training in the methodology (Pyzdek, 2003).
- Projects are usually chosen by the Master Black Belt, who should also be able to lead the project and train other belts (Stankalla, Chromjakova, & Koval, 2019).
- Sponsors are all the parties interested in the success of the project (George, 2002).
- And champions are the most business-oriented team members from key management who support the project execution (Antony, Gupta, Sunder M., & Gijo, 2018), (Mahanti & Antony, 2005).

Six Sigma has a positive impact on business objectives, process performance, flow, and quality (Kale, Katke, Dayane, & Thakar, 2022). Six Sigma has already proved its efficiency in process improvement in different industries (Ahmed, Page, & Olsen, 2020). However, the tools used in Six Sigma are currently undergoing changes due to the development of technologies.

Both approaches, Lean Manufacturing and Six Sigma, have proven themselves in a good way in various kinds of business and production processes (Yadav, Shankar, & Singh, 2020b). At the junction of two successful practices in the 2000s, the Lean Six Sigma approach has appeared, including the best practices of both approaches. Lean Six Sigma has the principle that: the activities that are critical to quality for the customer and have delays in time could be improved (George, 2002, p. 4). Lean Six Sigma creates a process that is "robust, reliable, consistent, and efficient" (Yadav, Shankar, & Singh, 2020a).

## 2.3 Lean Six Sigma and Industry 4.0

Even though Lean Six Sigma was successfully implemented in many companies, the development of technologies provides the impetus to question the future of Lean Six Sigma (Yadav, Shankar, & Singh, 2020b).

Several attempts have already been made in order to study the influence of Industry 4.0 on Six Sigma as a separate method; however, the amount of work is considerably low, and only a couple of authors have tried to examine the combination (Saidi & Soulhi, 2018), (Antony, et al., 2019), (Duc, a další, 2023), although it is possible to find papers combining Six Sigma with different Industry 4.0 technologies.

The combination of Lean as a separate method and Industry 4.0 has already been investigated by many authors, coming up with suggestions for the best possible practice of combining these two fields (Leyh, Martin, & Schaeffer, 2017), (Rauch, Dallasega, & Matt, 2016), (Yeen Gavin Lai, Hoong Wong, Halim, Lu, & Siang Kang, 2019), (Mayr, et al., 2018), (Wagner, Herrmann, & Thiede, 2017), (Dogan & Gurcan, 2018), (Kolberg & Zühlke, 2015).

However, the number of studies on the combination of Lean Six Sigma as a methodology and Industry 4.0 is comparatively low, with increasing interest as the topic is profound (Anvari, Edwards, & Yuniarto, 2020), (Sodhi, 2020), (Arcidiacono & Pieroni, 2018), (Bhat, Bhat, & Gijo, 2020). And as Lean Six Sigma has always been closely related to the technologies (Uriarte, Ng, & Moris, 2018), the fast development of technologies has a great influence on it, according to many theoretical and practical studies of contemporary authors (Ahmed, Page, & Olsen, 2020), (Ferrin & Muthler, 2002), (Chinbat & Takakuwa, 2008), (Celano, Costa, Fichera, & Tringali, 2012), (Yachao, 2008), (Börner & Uremovic, 2010), (Hussain, Campean, & Munive-Hernandez, 2019), (Abdallah, 2020), (Sekhar &

Mahanti, 2006), (Mahanti & Antony, 2005), (Mandahawi, Shihabi, Abdallah, & Alfarah, 2010), (Koppel & Chang, 2020), (Liverani, et al., 2019) and others.

The views on the applicability and suitability of Lean Six Sigma vary from being an essential part of industrial life in the near future (Uriarte, Ng, & Moris, 2018), (Yadav, Shankar, & Singh, 2020b), (Chiarini & Kumar, 2020), (Anvari, Edwards, & Yuniarto, 2020), (Bhat, Bhat, & Gijo, 2020) to losing its concepts due to the development of complexity (Palací-López, Borràs-Ferrís, da Silva de Oliveria, & Ferrer, 2020), (Saidi & Soulhi, 2018), (Anass, Amine, Ibtissam, Bouhaddou, & Elfezazi, 2021), (Ganjavi & Fazlollahtabar, 2023). Some scientists consider Lean Six Sigma a prerequisite for the successful introduction of Industry 4.0 technologies (Arcidiacono & Pieroni, 2018), (Chiarini & Kumar, 2020), (Anvari, Edwards, & Yuniarto, 2020), (Tissir et al., 2024). It was noted that the fourth industrial revolution provides an opportunity for continuous improvement methodologies (Arcidiacono & Pieroni, 2018), (Sodhi, 2020). Especially, this point of view was studied from the Lean perspective mentioned above (Mayr, et al., 2018), (Dombrowski, Richter, & Krenkel, 2017), (Rossini, Costa, Tortorella, & Portioli-Staudacher, 2019b).

At the same time, it is noted that LSS and Industry 4.0 share common interests, especially connected with data availability (Bhat, Bhat, & Gijo, 2020), (Sodhi, 2020), (Sordan, Oprime, Pimenta, Silva, & González, 2021), (Skalli et al., 2023b), (Rifqi et al., 2024). As Lean Six Sigma has a strong statistical compound, data collection and analysis constitute an integral part of the methodology, as it is a must for process improvement. Improvements in production efficiency and defect reduction, discussing the role of advanced Industry 4.0 tools in optimization of DMAIC process, have already been mentioned by several authors, including Duc et al. (2023) and others.

### 2.3.1 Lean Six Sigma, Industry 4.0, and data analytics

Key Industry 4.0 technologies to improve decision-making, reduce costs, and streamline operations, leading to significant competitive advantages, are artificial intelligence, machine learning, big data analytics, automation, industrial robots, and smart sensors (Ibrahim & Kumar, 2024). The advancement of these technologies allows the collection of more data with the help of RFID and sensors, and the analysis of large amounts of data becomes easier, which will lead to better decisions (Gupta, Modgil, & Gunasekaran, 2020), (Sodhi, 2020).

In Industry 4.0, the data processing of large amounts of data is called Big Data and Data analytics. This aspect has a major influence on Lean Six Sigma methodology and has been analyzed by Dogan and Gurcan in 2018 and by Gupta, Modgil, and Gunasekaran in 2020. Apart from analysis of Big Data on Lean Six Sigma, the existing data mining techniques were also analyzed in the papers with particular emphasis on the Process Mining method, as Lean Six Sigma "focuses on the quality in a process." (Dogan & Gurcan, 2018). It was concluded that the emerging data analysis techniques with data mining tools would serve as an advantage for Lean Six Sigma methodology, as the amount of data available for the analysis will increase, and the voice of the customer will be collected automatically.

Big data could also positively influence Lean Six Sigma projects when decisions are made to avoid unnecessary costs (Gupta, Modgil, & Gunasekaran, 2020). The necessity of the framework for the companies to combine Big Data Analytics, Lean Six Sigma, company, and customer demands was noted by Gupta, Modgil, and Gunasekaran (2020). It was also stated that the widespread use of programs able to calculate big data sets will influence Lean Six Sigma, especially from the Design of Experiments point of view, as the main parameters would be calculated automatically (Sodhi, 2020). Moreover, some authors also stated the point of view that with the advancement of data analytics, Six Sigma tools might become obsolete, but the qualitative approach connected with the competencies of Lean Six Sigma specialists will retain its significance (Sodhi, 2020).

To enhance the data analysis processes, other Industry 4.0 technologies possess significant potential. Here, an important influence might be given to artificial intelligence (AI) and augmented reality (AR), which will allow real-time data analysis, predictive maintenance, and improved process visualization (Sordan, Oprime, Pimenta, Silva, & González, 2021), thus making the data analysis process faster and more reliable.

Based on the development of the technologies mentioned above, several frameworks for the integration of Lean Six Sigma (LSS) with digitalization for enhanced Industry 4.0 environments have already been offered. Such as the HyDAPI framework, developed by Clancy et al. (2024), that merges traditional process improvement methodologies from LSS with real-time data analytics and advanced digital technologies, such as IoT and artificial intelligence, to create a data-driven, adaptive system for managing production processes (Clancy, Bruton, & O-Sullivan, 2022).

### 2.3.2 Lean Six Sigma and Industry 4.0 in different fields

The analysis of the confluence of Lean Six Sigma and Industry 4.0 was also made for particular fields, namely, healthcare (Arcidiacono & Pieroni, 2018), sustainability (Titmarsh, Assad, & Harrison, 2020), (Kaswan et al., 2023) sustainability (Kaswan et al., 2022), (Khanzode et al., 2021), and maintenance (Antosz & Stadnicka, 2018). The combination of Lean Six Sigma and Industry 4.0 was noted to positively influence the quality, efficiency, and flexibility (Antosz & Stadnicka, 2018) in the maintenance service process, but the proposed methodology was in the implementation stage, and the authors planned to continue the research with the data that was collected.

In healthcare, the role of data analysis is worth considering as well; thus, the analysis of the process in the Emergency Department proved the positive effect of the combination of Lean Six Sigma and Industry 4.0, as new technologies allow for better data collection and Lean Six Sigma provides a basis for the necessary information extraction (Arcidiacono & Pieroni, 2018), combining LSS with advanced digital technologies can streamline patient care processes, reduce waste, and improve service delivery.

Several research gaps were mentioned in the analysis of the combination of Lean Six Sigma and Industry 4.0 for sustainability, namely the assessment of the environmental effect of the confluence, the research on life cycle rather than product, and the influence of data on methodology (Titmarsh, Assad, & Harrison, 2020). However, the complementary nature of the conjunction has also been identified (Kaswan et al., 2022), (Khanzode et al., 2021). A foundational framework for companies aiming to adopt GLSS in Industry 4.0 contexts to drive both ecological and operational improvements was proposed by (Letchumanan et al., 2022). These insights might positively influence the future of industrial companies trying to improve their green footprint.

Another interesting work was done by (Skalli et al., 2023a) investigating the combined effect of Lean Six Sigma (LSS), the Circular Economy (CE), and Industry 4.0 technologies on sustainable manufacturing performance, where it was concluded that Industry 4.0 supports LSS, which, in turn, positively impacts sustainable operational performance. However, Industry 4.0’s direct effect on CE is minimal, suggesting that LSS acts as a key mediator between digital innovation and sustainable practices (Skalli et al., 2023a).

The aspect of the influence of the conjunction on the supply chain management has also already been analyzed. Jayaram (Jayaram, 2016) demonstrates how combining Lean Six Sigma with Industry 4.0 and the Industrial Internet of Things (IIoT) can enhance global supply chain management. The integration of these technologies optimizes processes, reduces defects, and creates an autonomous supply chain, leading to higher efficiency and sustainability through real-time data and predictive analytics (Jayaram, 2016), (Sahoo & Upadhyay, 2024). The independent studies mentioned above stated the necessity to better understand the influence of Industry 4.0 on Lean Six Sigma.

The integration of Lean Six Sigma into the design of the Cyber-physical system was proposed by Michael Sony in 2020. As the creation of CPS is the core of Industry 4.0, the framework for its implementation might provide the necessary insight. Thus, the author tries to answer this research gap and propose the integration of Lean Six Sigma methodology for the 5C and 8C system architecture (Sony, 2020). In the work, the author also states future research perspectives for CPS, Lean Six Sigma tools, and their future usage to improve customer satisfaction.

### 2.3.3 Lean Six Sigma and Industry 4.0 conjunction challenges

It is important to mention that the emerging conjunction possesses some challenges that should be considered, despite the fact that the opportunities provided by the conjunction of LSS and Industry 4.0 could provide greater benefits (Efimova & Briš, 2022). Several barriers were highlighted already, such as high implementation cost, data-related challenges, the lack of strategic vision, long-term commitment from management, and the training associated with the new technologies and skill gap (Macias-Aguayo et al., 2022; Rajak et al., 2024), (Vinodh & Shimray, 2022), (Zulfiqar et al., 2023), (Antony, Vinodh, & Chakraborty, 2024).

An interesting study was also performed where the Delphi method was applied to gather the ideas from the experts, and the key barriers were identified as data security concerns and a lack of skilled and trained personnel (Vimal et al., 2023).

In this research, the D-TISM approach was used to create a hierarchical structure in which the connections among these barriers could be observed. Thus, there is a need for a simple, clear IT infrastructure and targeted personnel development. The findings offer a strategic roadmap for practitioners and managers who are willing to successfully adopt Industry 4.0 technologies within LSS, which might lead to improved operational performance and organizational efficiency.

To sum this up, despite all the positive impacts mentioned above and the potential of the conjunction of Lean Six Sigma methodology and Industry 4.0, it should be kept in mind that, as with many other improvements, the introduction of the conjunction is connected with certain challenges.

### 2.3.4 Success factors of Lean Six Sigma and Industry 4.0.

The more challenges are analyzed, the more factors influencing the success should become visible. The conjunction of Lean Six Sigma and Industry 4.0 has the critical success factors that have already been investigated, and their hierarchy was proposed (Yadav, Shankar, & Singh, 2020a), (Yadav, Shankar, & Singh, 2021), (Khourshed, 2023), (Kumar et al., 2024), (Samanta et al., 2023). The critical success factors were identified based on the literature review and questionnaires.

The key enablers that were identified are strong management commitment, a supportive organizational culture, and structured LSS methodologies that align with Industry 4.0’s technological advancements (Yadav, Shankar, & Singh, 2020a), (Khourshed, 2023). A similar analysis on the success factors was done by (Wankhede et al., 2024), where critical factors were identified as the principles of both Lean and Six Sigma as the core of the methodology, workforce skills and training, performance measures to track progress and success, management commitment, and proper organizational readiness. The authors state that in order to be successful in the market, these key factors are of great importance when there is a need to introduce new technologies to the LSS projects. The hierarchy of critical success factors was proposed by Yadav, Shankar and Singh (2021), and a need to evaluate the mutual influence of Industry 4.0 and Lean Six Sigma was stated.

### 2.3.5 Lean Six Sigma and Industry 4.0 influence

In the contemporary situation, there are still several open topics connected with the influence of Lean Six Sigma, Industry 4.0, and their conjunction on the existing practices.

Thus, it has not been concluded yet what influence is more efficient for the companies – the influence of Lean Six Sigma, the influence of Industry 4.0, or their synergy. Interesting work was proposed by Rossini, Costa, Tortorella, and Portioli-Staudacher (2019b) where it was noted that currently, the effect on the process improvement is greater provided by Lean than by Industry 4.0. The majority of studies stated that Industry 4.0 has a positive impact on Lean Six Sigma, but the effectiveness (ROE) of the usage of the combination has barely been estimated (Sodhi, 2020). Moreover, the difference in the influence on SME and large companies has not yet been analyzed, and the necessity was stated by Anvari, Edwards, and Yuniarto (2020). Moreover, there is a limited focus on specific technologies within Industry 4.0, such as the Internet of Things (IoT) and artificial intelligence (AI), and their direct impact on LSS outcomes (Tissir et al., 2022).

The aspect that should also be mentioned here is some specifications that might arise connected to the topic with different sizes of enterprises. As Lean Six Sigma is not as widely spread in SMEs as in large companies, the influence of the conjunction of LSS and Industry 4.0 on SME also provokes special interest. As it was noted by Alsaadi (Alsaadi, 2024), combining Lean Six Sigma (LSS) with Industry 4.0 in small and medium enterprises (SMEs) is challenging because of the factors such as resource limitations, a lack of in-house expertise with advanced technologies like AI and IoT, and cultural resistance to change, all of which hinder adoption and effectiveness. Additionally, SMEs struggle to align LSS's focus on efficiency with the data-driven nature of Industry 4.0 and face difficulties in managing large data volumes, requiring tailored strategies, external expertise, and government support to overcome these roadblocks (Alsaadi, 2024).

Thus, it could be seen that the major influence on Lean Six Sigma methodology is provided by the rapid development of technologies and increasing access to big data and data processing. However, the future perspectives of Lean Six Sigma are not absolutely clear, and a better analysis of the problem is required. Despite several attempts to analyze Lean Six Sigma and Industry 4.0 in chosen industries and the development of the integration models, the research on the conjunction of the two notions is still in its infancy.

### 2.3.6 Lean Six Sigma and Industry 4.0 perspective

Despite the fact that the confluence of Lean Six Sigma and Industry 4.0 has already existed for some time, there are still some open, up-to-date topics that have not yet been covered. In the year 2025 it can be seen that the interest towards the topic remains and is developed form several perspectives, namely currently it is required to move beyond the theoretical foundation, with the data gathered from the practical field, to set up the clear framework of the conjunction and to focus on a human compound in the conjunction of Industry 4.0 and Lean Six Sigma, thus creating an inextricable connection with Industry 5.0 (I5.0) concept.

First, it should be noted that despite the deep theoretical analysis of the topic, the systemic validation and framework creation are still lacking in the current environment. Moreover, the empirical validation of the theoretical assumptions is still scarce in the literature on the LSS and I4.0 topic. Recent research argues that despite the fact that the core components have already been defined, a systematic, practically validated framework to merge them is still missing. Thus, Hossain and Purdy (2025) state in their research that there is a gap in the framework that is able to merge the two notions. In their work, they propose the Lean 4.0 approach, stating the need to further validate it empirically. Another piece of work, stating that a conceptual framework is missing, is the work of Antony et al. (2025), where they state that the governance of the transition in this field is missing. In this work, the missing framework is targeted at an attempt to provide a clear picture of the theoretical and practical fields.

Another aspect currently targeted in the recent research is the transition to predictive LSS, rather than being only a reactive optimization instrument. With the usage of digital twin and Big Data, there appeared an opportunity to use LSS tools to be more responsive to the changing environment. Performance variance could be explained with the help of Digital Twins, as was stated by Hosain and Purdy (2025), where the research mentions that the LSS should move from being a “static statistical tool” to “dynamic real-time simulation”.

Apart from having the potential to be a predictive and dynamic tool, LSS can also be moved from being a waste reduction method towards the “incremental innovation" introduction method with DMAIC tools, and AI combined (Elmarzouki & Jiuhe, 2025). In this research, the application of Digital Tween and AI is also analyzed to better understand future opportunities of the conjunction.

The last aspect, which is currently actively discussed in the literature, is concerned with LSS, I4.0, and the human aspect. As I4.0 is purely technocratic, there is a new concept introduced with a human-oriented nature – Industry 5.0. As it has already been stated above, a huge influence in LSS is provided by the human aspect, as I4.0 factors can substitute for theoretical concepts, but the creative concept is better covered by humans so far; thus, LSS could serve as a perfect methodology to close the gap between Industry 4.0 and Industry 5.0. In their work, Chichi & Mamad (2025) argue that LSS could provide the "human-centric" approach that, added to I4.0 technologies, could create the working framework. They explicitly state that research with the analysis of this aspect is required. A human-centered model is also presented in Alsadi et al. (2025) research, where the authors argue that the human aspect that influences efficiency is neglected with optimization using I4.0, and could be targeted by LSS. Methodology. Thus, as can be seen, the field is still transitional, and the given research is also targeted to understand the influence of the human aspect in conjunction.

# 3. METHODOLOGY

This section of the dissertation describes the methodological approach utilized to empirically investigate the relationship between Industry 4.0 technologies and Lean Six Sigma methodology, as well as the influence of advanced technologies on the LSS project's success. It provides a comprehensive overview of the research design, detailing the specific sampling techniques and data collection methods implemented to ensure the reliability and validity of the findings. Furthermore, it specifies the statistical instruments employed for data analysis.

## 3.1 Research design

The study comprises exploratory and explanatory studies. According to Tegan (Tegan, 2021) exploratory research is a method that allows for researching a topic in depth, which allows for gathering initial insights and a better understanding of the issue that is being dealt with. As the general idea is to keep an open mindset, this type of research allows the researcher to investigate innovative directions in various fields, including more innovative topics (Smith, 2024).

As the exploratory research can be used when the research topic is not clear, and the knowledge on the topic is general (Tegan, 2021) the given research method is used in the study to gather the primary information. In the given research, an exploratory study was done as a literature review, and an initial survey was conducted, which allows for the creation of a basic framework for the topic and sets up boundaries for the research. As the exploratory research helps to identify research questions (Saka et al., 2023) rather than state the reasons for the functioning of different processes, the same tactic was used in the study. Namely, the exploratory research was used to identify the research questions and research gaps that were further used to be measured as part of the explanatory study.

Explanatory research is more structured in nature, connected with statistical analysis, structured approaches for qualitative and quantitative research, and hypothesis testing. This method explores the causes that influence the given topic rather than gathering general information (Tegan, 2021). Here, the explanatory method was used to measure the statistical compound of the research, where an attempt was made to measure the influence of the Industry 4.0 technologies and company characteristics on the success of Lean Sex Sigma projects.

## 3.2 Research approach

To better understand the boundaries and set up the framework of the research, as well as the structure of the empirical research, an analysis of existing studies was performed. The research was developed in a way to create a better understanding of the influence of the development of technologies on the success of Lean Six Sigma projects. To achieve this goal, the research is composed of two parts: quantitative and qualitative.

The study uses a non-experimental research approach to explore the relationships between Lean Six Sigma project success and Industry 4.0. This study consists of qualitative research to answer open questions of the research, and quantitative research that comprises hypothesis testing on the topic of the influence of Lean Six Sigma on Industry 4.0 introduction. Together, both parts will help to analyze, generalize, and predict the influence of the development of technologies. The research comprises the usage of data that was gathered deliberately to answer research questions from primary sources. The data collection technique includes the quantitative survey instrument - a questionnaire. Since the population census is not reachable in this case, probability sampling and generalization were used in this study.

### 3.2.1 Qualitative research

Qualitative research is a research method that focuses on interpretation, meanings, and observation (Kemparaj & Chavan, 2013). The data in qualitative research is not assessed numerically as in quantitative research. Thus, qualitative research is usually based on the experience of the participants, when the analysis enables us to create an explanation of the phenomenon at hand (Silverman, 2011). Qualitative research is done to understand particular patterns rather than measure them. Despite the subjectivity connected with this research method, an unstructured or partially structured approach for data gathering allows a researcher to enrich the insights on the topic and lead flexible research, thus providing an opportunity to consider the emerging data as well.

In this research, a qualitative part is integrated as there is a need to consider how much the integration of Industry 4.0 within LSS methodology may vary from company to company. As the quantitative research can assess the predefined metrics and is connected with the standardized data analysis, the complexity of the topic might be omitted, and the perspectives that are related to the variance will not be considered. Therefore, qualitative methods seem to be more appropriate for exploring the contextual and subjective dimensions.

### 3.2.2 Quantitative research

The assessment of numerical and statistical data was done in the scope of quantitative research. The data for the analysis is thoroughly collected in order to identify patterns and relationships with the help of standardized tools. A typical advantage of quantitative research is that it possesses higher objectivity, as the results are based on the measurement of numeric data (Significance of Quantitative Research: 9 Essential Insights, 2025), but it is not considered that the reality is dynamic.

In this research, the quantitative part will be aimed at the data collection on the usage of Lean Six Sigma and Industry 4.0 in industry. The data analysis is performed in order to understand the associations, based on which the influence of company culture and Industry 4.0 technologies on Lean Sex Sigma project success will be assessed.

For the quantitative part of the research, the following overall hypotheses were used to test the research questions:

*$H_0$(1) None of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a budget perspective.*

*$H_A$(1) At least one of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a budget perspective.*

*$H_0$(2) None of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a time perspective.*

*$H_A(2)$ At least one of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a time perspective.*

*$H_0(3)$ None of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, influences project success from an efficiency perspective.*

*$H_A(3)$ At least one of the company's characteristics, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from an efficiency perspective.*

*$H_0(4)$ None of the project's characteristics, such as project duration, project budget, and number of project participants, influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_A(4)$ At least one of the project's characteristics, such as project duration, project budget, and number of project participants, influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_0(5)$ None of the Industry 4.0 technologies influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_A(5)$ At least one of the Industry 4.0 technologies influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_0(6)$ There is no correlation between the number of Industry 4.0 technologies and project success.*

*$H_A(6)$ At least one of the project's characteristics, such as* project duration, project budget, and number of project participants, *influences LSS project success (from a budget, time, and efficiency perspective).*

### 3.2.3 Triangulation

To provide a more comprehensive understanding of a complex problem, the use of both qualitative and quantitative research approaches was used, also known as triangulation (Significance of Quantitative Research: 9 Essential Insights, 2025). Here, the qualitative approach provides an understanding of the background and reality, whilst the quantitative approach provides statistical confirmation of the topic. Thus, results achieved while applying both approaches deliver a better understanding of the topic of the dissertation and allow for more detailed research.

Qualitative research is performed to get an in-depth understanding of the current situation and to set up the background of the research. The aim is to collect detailed information with the help of the semi/structured interview and to answer the “why” and “how” questions to bring better insights for the quantitative part of the research. The qualitative aspect will be exploratory, and it will involve sampling views from respondents.

Quantitative research involves working with data and statistical analysis. The data for the given research is gathered from primary sources with the statistical tool survey. Quantitative research is explanatory and involves statistical methods for gathering data measurements.

This research combines quantitative and qualitative approaches to achieve several purposes. First of all, the applied triangulation allows for cross-checking the findings from different sources, thus ensuring the reliability of the results. Secondly, the application of both approaches provides deeper analysis with richer details and an emphasis on the details that one approach may miss. Thirdly, it finds out the contradictions and discrepancies, together with unexpected results, where the following consideration and/or broadening of the scope of the research could be motivated. Therefore, this approach allows for better analysis of various factors that are connected with the introduction of Industry 4.0 technologies into industrial companies for LSS projects.

## 3.3 Data Collection Methods

The data collection approach is crucial for any research as it ensures both credibility and accessibility within the research setting. This research employs both primary and secondary data to ensure a comprehensive foundation for the analysis.

Primary data for the research were gathered for a specific purpose to answer the research questions. The primary data can be collected with the help of surveys and studies created deliberately for the given research. For this dissertation, primary data comprises a major part of the analysis. The primary data collection method used for this research was interviews with industrial managers and specialists dealing with optimization processes. To be able to keep the participant's focus on the topic, a structured in-depth interview approach was employed, where the interview is directed by a specific set of questions, which shape and control the flow of the conversation to ensure relevance to the research objectives. Another source for the primary data for the research was a questionnaire that was composed of both open and closed questions. The questionnaire provided data for the statistical analysis.

Secondary data was also used for this research, namely, to set up the research background and to assemble the details on the existing gaps and future perspectives. Secondary data is considered to be data gathered from different external and internal sources, such as books, reports, and research articles. For this research, articles and books were used to provide a solid base for analysis.

## 3.4 Sampling method

A questionnaire was developed for this study as a survey instrument, based on the literature review and research questions. Since the new survey instrument was developed for this study, a pilot study was performed with the open questions, which provided useful information for the final survey instrument. The results of the pilot study were used for the creation of the final questionnaire. In the final research instrument, dependent and independent variables were incorporated into the questionnaire.

The process of data gathering is aimed at companies involved in different industries in the Czech Republic. The aim is to collect the maximum data possible through the questionnaire data collection. The size of the company was not limited; thus, SME were included as well as large companies. Considering the total number of companies in the Czech Republic, the whole population analysis is not possible; thus, a sampling analysis was chosen in the given case. The country serves as an ideal source for the analysis of industry, as currently the

Czech Republic is one of the developed industrial countries in the middle of Europe that actively participates both in eastern and in western markets.

The research combines the qualitative part, which is based on the systematic literature review and structured interview method, and the quantitative part, which is connected with the testing of hypotheses. Every hypothesis is measured depending on the parameters. The method of hypothesis testing follows the idea presented in the course “Data Analytics for Lean Six Sigma” on Coursera (Zwetsloot, 2021) that was enriched with the statistical analysis methods for the ordinal variables, as in the given study, the Y-variable was gathered and assessed based on a given 5-scale parameters (Salkind, 2010; Sullivan & Artino, 2013). The combined approach is performed in Table 1. In the table, the Y variable is the dependent variable that is measured in the analysis, and the X variable is the independent variable influencing the Y variable.

Table 1. Hypothesis testing. Modified from "Data Analytics for Lean Six Sigma" course (Zwetsloot, 2021)

| | **Numerical Y** | **Categorical Y** | **Ordinal Y** |
|---|---|---|---|
| Numerical X | Regression analysis | Logistic regression | Ordinal logistic regression |
| Categorical X | ANOVA/t-test | Chi-square analysis | Mann-Whitney U, Kruskal-Wallis |
| Ordinal Y | Spearman | Logistic/Multinomial logistic | Spearman r correlation |

To perform statistical analysis and to visually display the results, the program for descriptive statistics, SPSS, is used in this research. The statistical significance of the estimated variable is evaluated at a 95% confidence level. Accordingly, in this study, the null hypothesis is rejected when the p-value that was calculated in the statistical analysis is less than 0.05.

As one of the results of the research is the concept of the system of the conjunction of Lean Six Sigma and Industry 4.0, the idea of the concept is presented in Table 2.

Table 2. The concept of the system of the conjunction of LSS and Industry 4.0. Source: own research

<table>
<tr><th>Literature review</th><th>Own research</th></tr>
<tr><td colspan="2">What Industry 4.0 technologies are used for LSS projects</td></tr>
<tr><td>Big Data, Simulation, Cyber-Physical Systems, Robotics, Augmented Reality, Artificial Intelligence, Cloud computing, Internet of Things</td><td></td></tr>
<tr><td colspan="2">What are Industry 4.0 technologies used for</td></tr>
<tr><td>Analysis of trends, root causes, and inefficiencies; Measurement of real-time data; Training; Monitoring and real-time control; Setup and maintenance; Mapping</td><td></td></tr>
<tr><td colspan="2">Barriers connected with the Industry 4.0 introduction</td></tr>
<tr><td rowspan="6">Lack of management commitment, insufficient investment/resources, technical factors, training, clear strategy and framework, skills (digital, analytical, learning), organizational culture, and continuous improvement</td><td>As for the price</td></tr>
<tr><td></td></tr>
<tr><td>As for the duration</td></tr>
<tr><td></td></tr>
<tr><td>As for the efficiency</td></tr>
<tr><td></td></tr>
<tr><td colspan="2">Industry 4.0 technologies that have the biggest influence on the LSS project success</td></tr>
<tr><td rowspan="6">Big Data analytics; Simulation; CPS; robotics, AI, IoT</td><td>As for the price</td></tr>
<tr><td></td></tr>
<tr><td>As for the duration</td></tr>
<tr><td></td></tr>
<tr><td>As for the efficiency</td></tr>
<tr><td></td></tr>
<tr><td colspan="2">Is LSS and Industry 4.0 a beneficial conjunction</td></tr>
<tr><td>Yes</td><td></td></tr>
</table>

# 4. RESULTS

This chapter provides a comprehensive presentation of the data analysis results. The findings derived from the data analysis are discussed and examined in relation to the study's objectives of the given research. Furthermore, the findings are contextualized within the context of the relevant existing literature, offering a deeper perspective on their theoretical and practical implications.

## 4.1.1 Industrial companies' background

The understanding of companies' profiles, participating in the research, is crucial for the interpretation of the research results. Companies' attributes provide background information and help in understanding the trends and insights revealed through data analysis. Accordingly, this study assessed various background features of the participating organizations. In total, the questionnaire was sent to 1267 companies, and the feedback was received from 82 companies in total. However, the final number of responses included in the analysis was 62 companies, yielding an almost 5% response rate from the initial number of sent questionnaires and contributing meaningful data to the research. The organizational characteristics considered in the research include company size, company profile, and the level of expertise in both Lean Six Sigma and Industry 4.0. The details of the results on these factors are elaborated on further.

***Company size***

Regarding the characteristics of the organizational scale, among all companies that participated in the research, a total of 62 companies provided valid responses to the question about company size. A detailed segmentation of this sample reveals that the majority of respondents, namely 37 participants (constituting 59% of the total number), were representatives of small or medium-sized enterprises (SMEs). The remaining 25 participants (accounting for 41% of the sample) were representatives of large enterprises. Consequently, this distribution constitutes a balanced research sample that considers the perspectives of both SMEs and large enterprises. This diversity is important for this study, as the influence of company size on the LSS project success was evaluated as part of the quantitative research.

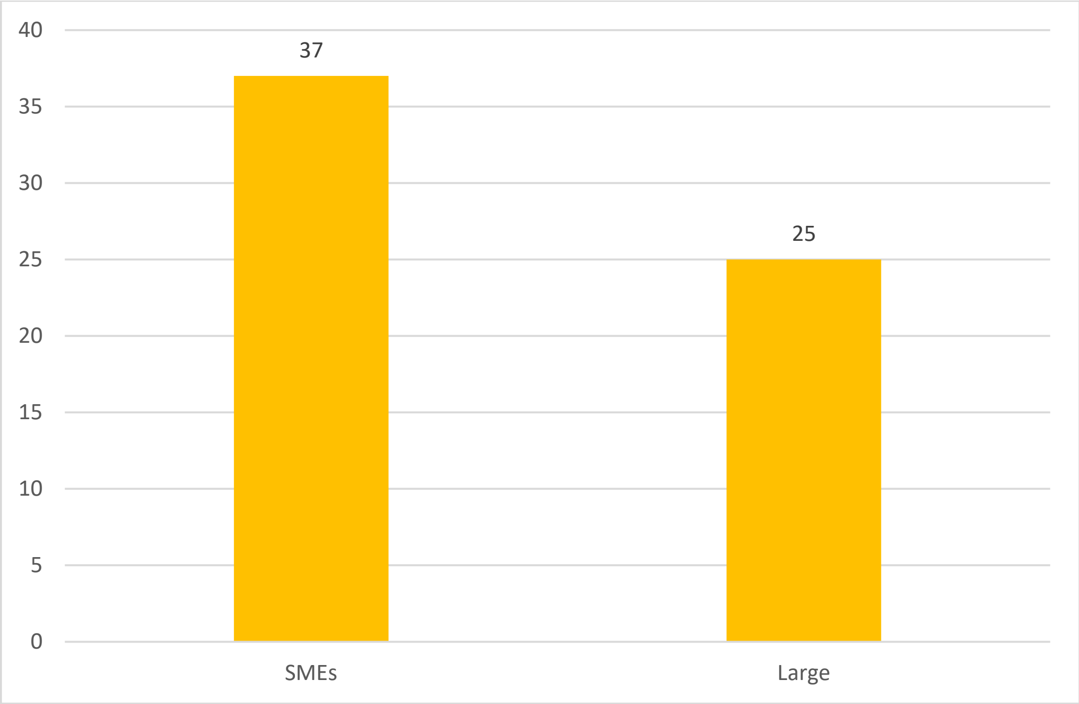


*Figure 1. Company size. Source: Own research*

***Company profile***

Given that the research was conducted in the industrial landscape of the Czech Republic, establishing the profile of the participating companies is essential for understanding the context of the findings. The demographic study reveals that among the 62 participating organizations, the majority of respondents operate in the Automotive and Engineering and manufacturing industries, accounting for 25.8% and 24.2%, respectively. These primary sectors were followed by the Chemical and Food industries (8.1% each) and the Textile and Wood processing industries (4.8% each). The remaining industries represented in the survey were not represented in sufficient numbers and, consequently, are not considered separately in the detailed analysis. The important fact here is that this classification is not merely descriptive, but it is also evaluated from the perspective of the influence of the company's profile on LSS project success in quantitative analysis.

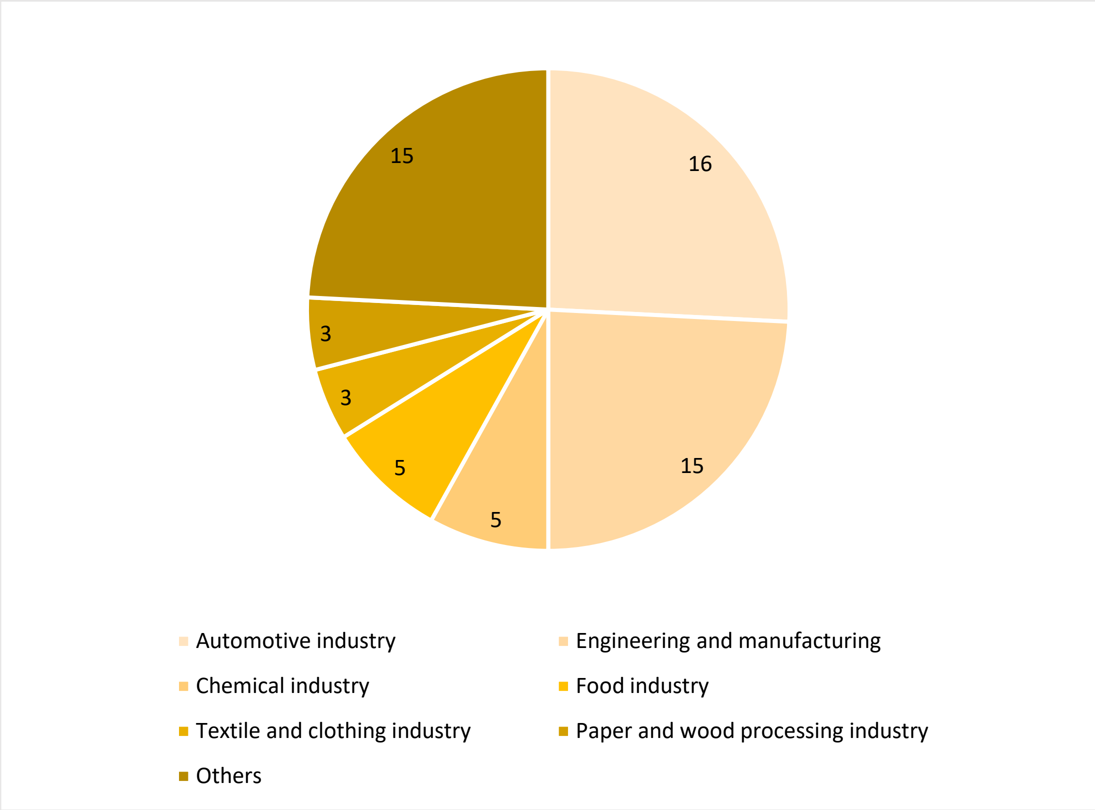


*Figure 2. Company profile. Source: Own research*

***Company experience with Lean Six Sigma***

Regarding the companies' experience with Lean Six Sigma, the data reveal that not all the companies that participated in the research have profound knowledge of Lean Six Sigma. It must be noted that 23 participating companies couldn't clearly report their experience with Lean Six Sigma, as in the research, there was no consideration of the separate usage of these methodologies; however, all of the participants of the survey have optimization processes implemented in the company. Conversely, among the companies that possess the LSS experience, long-term practitioners form the majority. Thus, the organizations that have experience of more than 15 years represent 29% of all participants (and 41% of the experienced subgroup). This data is vital for the study, as the analysis further evaluates whether LSS experience statistically correlates with the success of LSS projects.

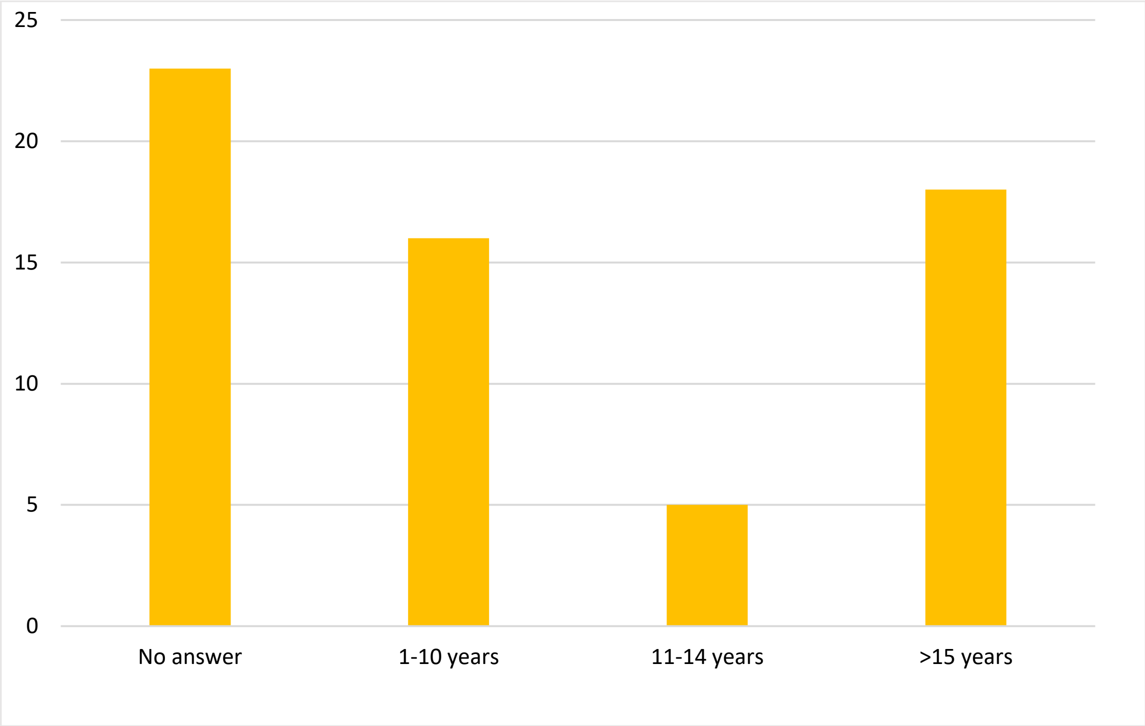


*Figure 3. Companies' experience with Lean Six Sigma. Source: Own research*

***Company experience with Industry 4.0***

As following important aspect, the experience in Industry 4.0 was also assessed in the survey, as the topic is inextricably connected with the research target. The results can be seen in Figure 4. Notably, a significant number of 25 participating companies provided indefinite responses, meaning that they either couldn't answer the question due to the conceptual complexity of the term Industry 4.0, or didn't have enough experience with Industry 4.0 to state otherwise. As Industry 4.0 is considered a complicated term, and no explanation or more detailed information was provided to clarify the understanding, companies might have faced difficulties answering the question. Among the respondents with quantifiable experience, the results are as follows: 31% have up to 5 years of experience, while 21% of the participating companies report between 6 to 10 years. Only a minority of 8% are experienced with Industry 4.0 for more than 10 years. This categorization is essential to the study as the analysis further in the research evaluates whether the experience with Industry 4.0 technologies acts as a predictor for LSS project success.

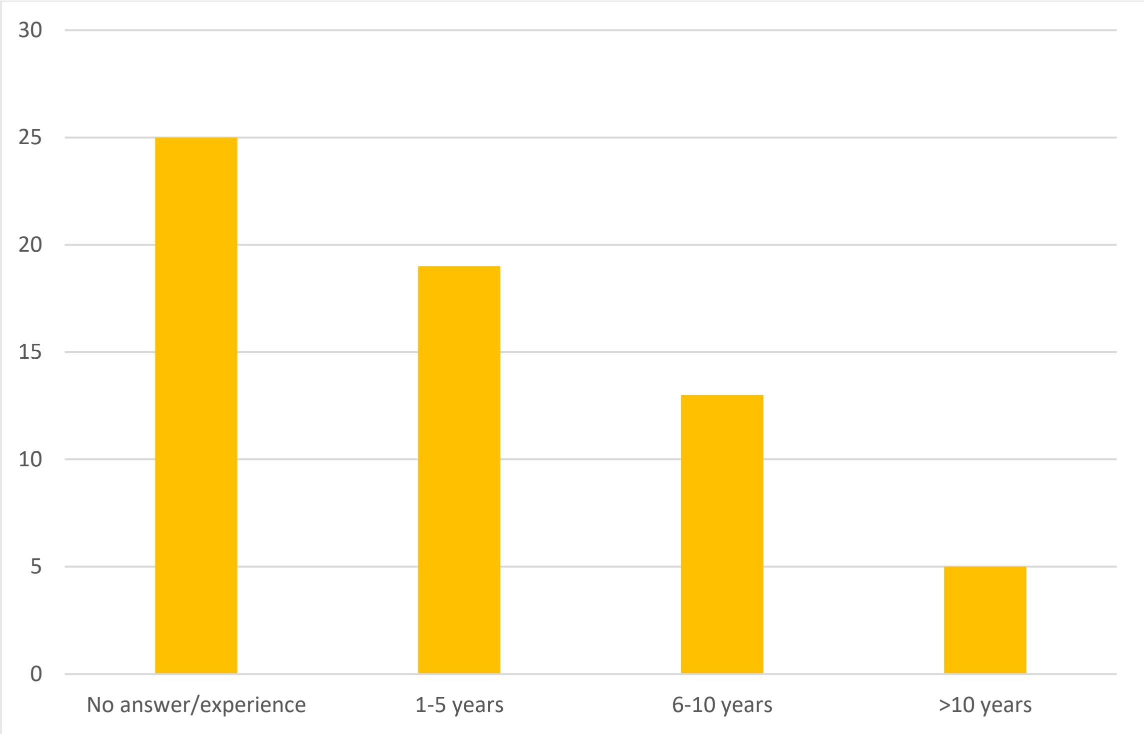


*Figure 4. Companies' experience with Industry 4.0. Source: Own research*

### 4.1.2 Companies' background from the pilot study

This part provides the details on the background of the companies participating in the Pilot phase of the given research. While the primary statistical evaluation focuses on the data gathered for the main research, the results from the pilot studies are included here to provide a comprehensive empirical context. These data are also important to be added here as the results from the pilot studies closely align with the results from the qualitative research that will be discussed later in the work, thus offering preliminary evidence of the synergy between Lean Six Sigma and Industry 4.0. Moreover, although these companies' answers are not integrated into the main research, their data serve as a vital comparative baseline, which helps to validate the theoretical potential of the conjunction of Lean Six Sigma and Industry 4.0 before the broader population of the main research is analyzed. Therefore, ignoring this part of the research would omit a significant layer of evidence. Instead, the results are presented here to establish a background context against which the results of the main survey could be better understood.

***Company size***

Regarding the organizational scale of the pilot study, a total of 45 valid responses were considered. Among all the companies that replied to the question connected with the company's size, 31 were representative of small and medium enterprises (which account for 69% of the total number). At the same time, only 14 answers were received from the large-sized companies (thus, constituting 31% of the total).

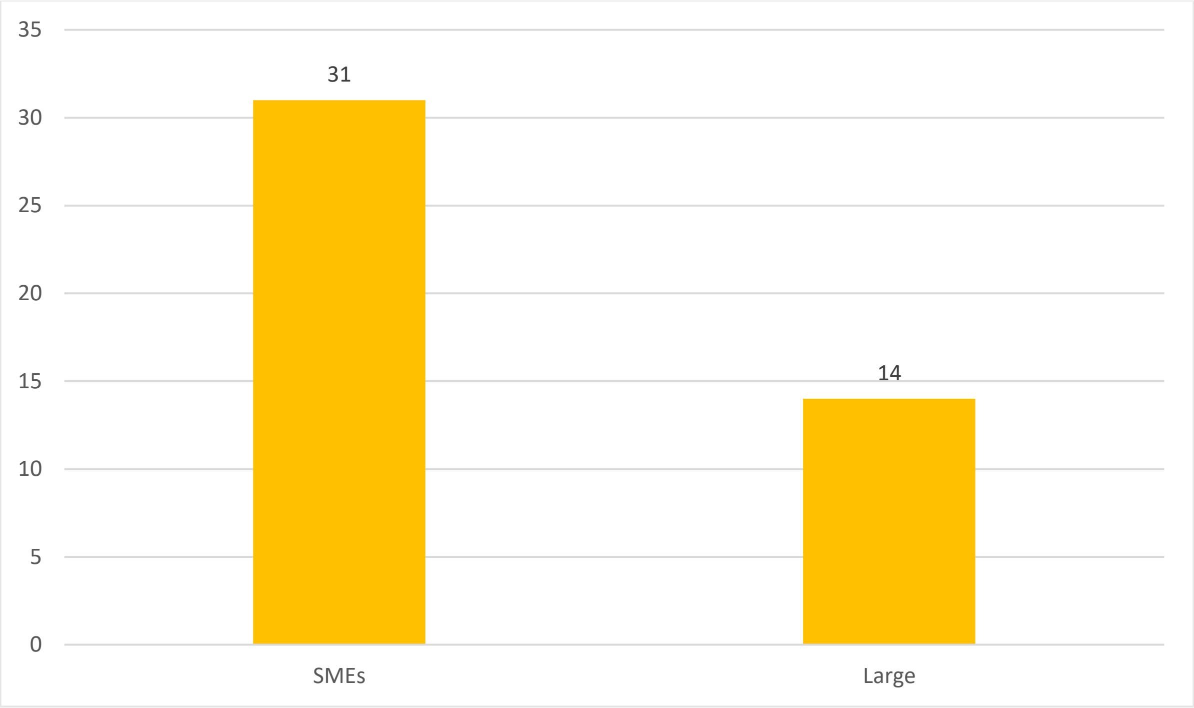


*Figure 5. Company size (Pilot study). Source: Own research*

***Company profile***

Regarding the company profile of the pilot study, companies from different sectors participated, and a total of 49 replies were collected in response to this question. The results show that an overwhelming majority of 43 participants, representing 88% of the sample, were from the industrial sector. In contrast, the service sector had a marginal representation of only 5 participants representing different services.

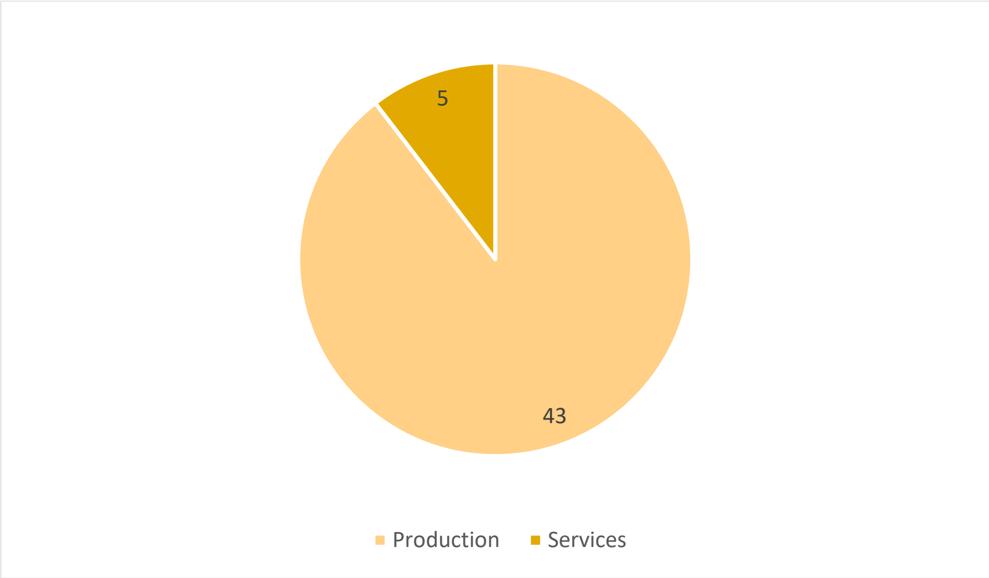


*Figure 6. Company profile (Pilot study). Source: Own research*

***Company experience with Lean Six Sigma methodology***

In the pilot study, the evaluation of the experience with Lean Six Sigma was evaluated as a binary assessment, where the presence or absence of previous experience was evaluated. Among the 44 participating companies that provided the valid data, the majority, 29 companies, demonstrated that they are experienced with Lean Six Sigma (constituting 66% of the total). At the same time, only 15 participating companies (34%) reported having no prior experience with the usage of the methodology (34%).

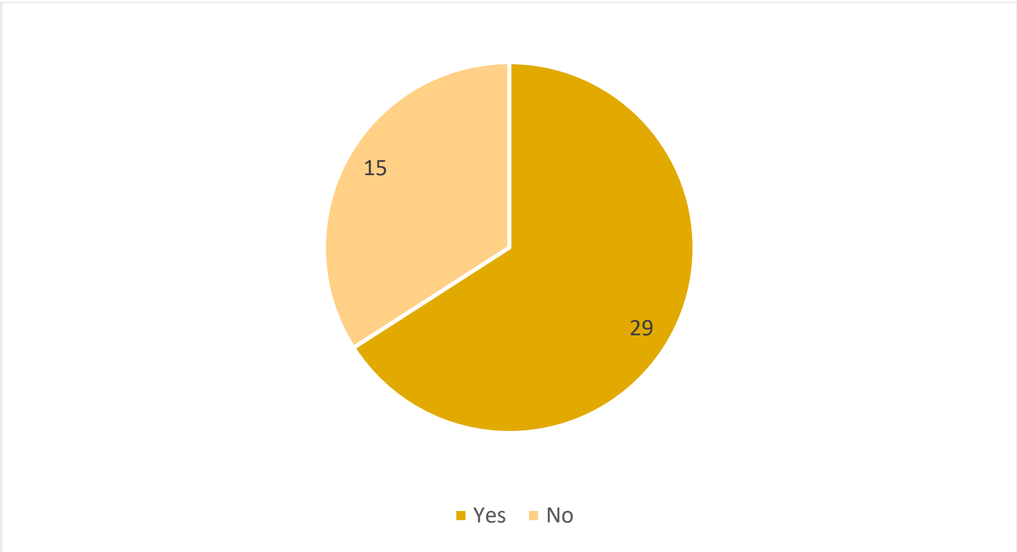


*Figure 7. Company's experience with LSS (Pilot study). Source: Own research*

### 4.1.3 Industrial companies' representatives' background

As the characterization of the industrial representatives who participated in the semi-structured interviews plays a crucial role in the validity of the qualitative findings, as they rely heavily on the expertise and strategic insights of the involved individuals, this part outlines the profiles of the participants interviewed during the qualitative phase. Thus, interviews were secured with 7 companies, and the sample size was secured because of the data saturation, when the data collected added little or no change to the information already gathered (Guest et al., 2006). The participants were all active professionals operating in the industrial sector. The demographic breakdown included two female and five male respondents, ensuring that the research incorporated perspectives from both genders.

Table 3. Sex or respondents, participating in the research. Source: Own research

| | **Number** | **Percentage** |
|---|---|---|
| Female | 2 | 28,6 |
| Male | 5 | 71,4 |
| Total | 7 | 100 |

The specific characteristics of the company were also considered in the research during the participant selection process. This was necessary to acknowledge because SMEs and Large companies often have different challenges that they see and accept from both Industry 4.0 and Lean Six Sigma, ranging from resource availability to project complexity. Thus, the total of 7 respondents who participated in the research comprised a balanced cross-section; four respondents were representatives of large companies, while three professionals represented Small and Medium Enterprises. This mix provided important insights for the qualitative part, as the combination allowed us to assess the topic from different points of view and to assess if any difference exists between the approaches existing in large companies and SMEs from the point of view of the conjunction of Lean Six Sigma and Industry 4.0.

## 4.2 Analysis of data gathered from the pilot study

This section presents the results of the pilot study, which was conducted in the form of a questionnaire comprising both open and closed questions. This format was reasonable in the given case, as the use of open-ended questions served as an important entry point, providing useful insights into the topic, while the closed questions helped to create the background for the research. Open questions then became a part of qualitative research. The qualitative approach was applied here as it allows for gathering a broad data capture and, thus, reducing the risk of leaving aside important aspects. The analysis is based on the concepts established during the previous literature review regarding the conjunction of Lean, Six Sigma, and Industry 4.0.

Considering the clear and useful insight provided by these preliminary insights, the pilot study results are also analyzed in this chapter. They contribute to the essential information that validates the research direction and support the subsequent creation of the practical framework for the conjunction of Lean Six Sigma methodology with Industry 4.0 technologies.

***How effective is the combination of Lean Six Sigma and Industry 4.0?***

As one of the central objectives of this research is to empirically evaluate the conjunction between Lean Six Sigma and Industry 4.0, an attempt to measure this conjunction was also made within the pilot study. To measure this relationship, the study determined how effectively these two terms could co-exist in the same environment. Respondents were asked to assess the potential effectiveness of the conjunction of LSS and Industry 4.0 using a 5-point Likert scale. On this scale, 1 represented ‘Not effective at all’, indicating a lack of synergy, while 5 represented ‘Very effective’, indicating a strong potential for integration.

The analysis revealed a high degree of variance in the perception, as the responses were distributed on the entire scale, meaning that each of the options from 1 to 5 was selected at least once by the participants. Despite this coverage, a particular central tendency emerged from the dataset, which is illustrated in Figure 8.

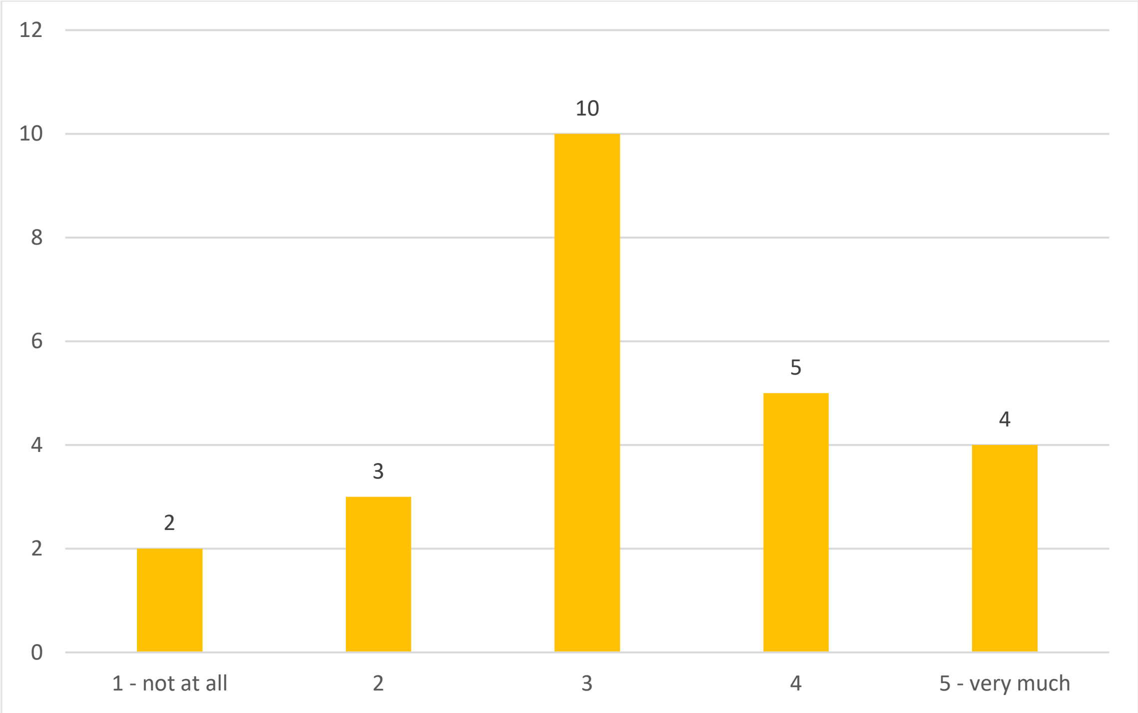


*Figure 8. How effective is the combination of LSS and Industry 4.0? Source: own research*

Quantitative analysis of the responses illustrated in Figure 8 indicates that 79.2% of the respondents perceive the conjunction of LSS and I4.0 as effective, with the score ranging from 3 to 5. Moreover, 16.7% of the respondents gave the highest possible level of positive influence to this question. However, the distribution of the answers also reveals an underlying uncertainty. The fact that the most popular response is the view that the conjunction is ‘effective in some situations’, rather than ‘very effective’, suggests that the implementation of the conjunction is not straightforward. Therefore, a more specific understanding of the conditions required for the effective combination of the LSS and Industry 4.0 conjunction needs to be clarified.

***What are the benefits of Industry 4.0 integration within the scope of Lean Six Sigma?***

One of the objectives of the qualitative part of the study is to identify the key contributors to the conjunction of LSS and I4.0 for the improvement process. The pilot study, thus, sought to find out which major tasks Industry 4.0 technologies can optimize within the scope of Lean Six Sigma methodology to support continuous improvement processes.

While the initial analysis revealed that different companies see the major advantages in different contexts, strong common trends rapidly emerged. While reviewing these trends in depth, major thematic tendencies were identified and summarized. From a methodological point of view, data saturation was achieved in the pilot study, as despite the fact that the collection process proceeded, new inputs ceased to appear, confirming that the key benefits were fully captured at that point in time. The specific comments provided by the industry specialists are provided below, translated into English for this dissertation.

*"Reduction of costs and complexity of processes, improvement of key indicators, overall higher work efficiency"*

*"long-term savings"*

*"Efficiency, productivity"*

*"A more modern approach, less laborious obtaining of results"*

*"Possibility to control and address weaknesses"*

*"Identifying and resolving bottlenecks."*

*"Digitization"*

*"Avoiding errors indirectly reduces costs in the long term."*

*"First of all, eliminating waste to the maximum extent possible. Improving and simplifying cooperation in the company, information, and clarity."*

*"Higher efficiency and more stable performance in meeting performance indicators."*

*"I don't know, but I suspect that the processes will become cheaper."*

Summarizing the qualitative input presented above, it becomes evident that the integration of I4.0 technologies within the scope of LSS methodology is not merely an additive process, but a transformative one. It should be noted that the major objectives for Industry 4.0 technologies should be aligned with the tenets of LSS, which are enhancing operational efficiency and long-term value creation.

In practice, this means that the technologies should be applied to streamline the value stream. The objectives are stated as follows: to achieve cost reduction, improve overall process effectiveness, and enhance cost-efficiency across various stages of production and delivery cycle. Moreover, the integration has a critical function in the early identification, monitoring, and management of bottlenecks and systemic inefficiencies. By implementing real-time data gathering, predictive analytics, and intelligent automation, Industry 4.0 technologies provide a robust foundation that is required to modernize and strengthen Lean Six Sigma methodology, ensuring that its tools will remain a powerful means for continuous improvement in the digital era.

***What Industry 4.0 technologies are used in the scope of Lean Six Sigma?***

The following step of the pilot study was dedicated to the study of a critical component, which is the identification and assessment of specific Industry 4.0 technologies used in the Lean Six Sigma methodology. The objective of this step is not merely to summarize the existing tools but also to evaluate their practical introduction and utility across the entire industrial spectrum of the Czech Republic.

To ensure a thorough analysis, the study comprises data from all organizations regardless of their size or profile. By including the full range of company types, from SMEs to large-scale companies, the study seeks to provide a clear picture of the Czech industrial environment. Apart from just stating the technological spectrum of the introduced technologies from the Industry 4.0 era, there was an attempt made in the study to establish a functional correlation between the core concepts of the given research, i.e., which Industry 4.0 technologies are used to support which specific Lean Six Sigma tools.

The analysis begins with a summary of all the Industry 4.0 technologies that are currently used in Czech companies. The summary of these technologies, together with the understanding of how popular they are currently in the market, helps to establish a clear picture of the technological environment in which Lean Six Sigma is shifting nowadays. The results of this summary are presented in Table 4.

Table 4. Industry 4.0 technologies in the Czech Republic. Source: own research

| **Industry 4.0 Technology** | **Mentioned as introduced technology** | **% to total respondents (50 answers total)** |
|---|---|---|
| IoT | 7 | 14 |
| Big Data | 10 | 20 |
| Cloud Computing | 15 | 30 |
| Robotics | 18 | 46 |
| Augmented Reality | 4 | 8 |
| Simulation | 16 | 32 |
| Additive manufacturing | 8 | 16 |

Although a significant proportion of the surveyed companies have already implemented the technologies to some extent, the data reveals a clear hierarchy in the adoption level. As the most widely implemented technology, there is Robotics having been integrated into the procedures of 46% of the participating companies. This technology is further closely followed by Simulation and Cloud Computing technologies. This adoption trend can be explained by the high operational utility of these technologies and the quick return on investment that these technologies offer. As these technologies were mentioned by both SME and large companies, they can be viewed as the foundational technologies that are available enough for SMEs and at the same time, are powerful enough for large companies. Robotics, as an example, can deliver immediate efficiency improvement through the automation of repetitive tasks, and its influence can easily be calculated. Simulation is also a tool that is not difficult to comprehend and implement; at the same time, it is considered to be an effective risk-mitigation tool as it allows companies to optimize processes in a virtual environment without high costs. Meanwhile, Cloud Computing is a necessary tool for digital infrastructure, as it allows for data storage and sharing between several participants, thus facilitating access and providing a resource for data analytics.

The pilot study further aimed at the intersection of the Industry 4.0 technologies and LSS methodology by targeting the topic of the particular Industry 4.0 technologies that are utilized for specific LSS tools. This proved to be a challenging assessment for the respondents, as the dataset was considerably lower than with other questions. This might prove the point that LSS tools are rarely employed in isolation, and thus, it is difficult to set up the boundaries between them. At the same time, the technologies usually cover several phases of the project, thus also creating a challenging task of separating the set one-to-one. The summary could be seen in Table 5.

Table 5. Industry 4.0 technologies are used for LSS. Source: own research

| **Technology** | **Answers** |
|---|---|
| IoT | 3 |
| Big Data | 2 |
| Cloud Computing | |
| Robotics | 3 |
| Augmented Reality | |
| Simulation | 1 |
| Additive manufacturing | 3 |

Nevertheless, this second step of the analysis revealed a slightly different set of priority tools. According to the results, it can be seen that for direct LSS application, the most frequently mentioned technologies are IoT, Robotics, and Additive Manufacturing. This could be explained by the fact that these technologies have a solid impact on data processing and physical process changes, making their link to LSS tools tangible.

Surprisingly, Cloud Computing and Augmented Reality were not mentioned by the respondents in the context of Lean Six Sigma. However, this absence should not be interpreted as evidence of irrelevance. On the contrary, these technologies may be specific to particular industries. For instance, Augmented reality is more relevant in sectors involving complex assembly, while Cloud Computing might be omitted due to its integration into broader IT infrastructure rather than as a direct LSS tool.

Table 6. Industry 4.0 technologies combined with LSS tools. Source: own research

| LSS tool | Technologies used |
|---|---|
| DMAIC | IoT, Big Data, Robotics, Additive Manufacturing |
| SIPOC | IoT |
| VSM | Robotics |
| TPM | IoT, Robotics |

An analysis of the frequency with which different technologies are applied to specific LSS tools allows us to see that the tool that currently uses the majority of Industry 4.0 technologies is DMAIC. By integrating IoT, Big Data, Robotics, and Additive Manufacturing, DMAIC acts as a center for digital transformation, where the data technologies are used for problem identification (IoT and Big Data) and physical technologies, such as Robotics and Additive Manufacturing, as tools to solve these problems. The integration of these technologies possesses a huge perspective for the future, as the data gathering and data analysis could be optimized, and open the door to partial or even full automation of some aspects of DMAIC analysis (Pongboonchai-Empl et al., 2025).

In contrast, tools like SIPOC, VSM, and TPM show a more focused technological direction. TPM combines with IoT and Robotics, thus creating a target of more automated and predictive maintenance. SIPOC is supported exclusively by IoT that can improve the digital tracking of process inputs. VSM is linked with Robotics, which could be linked with the fact that either robots are used to automate the systems or as the major tool that is implemented based on the VSM.

### *The results of the pilot study*

In conclusion, it can be summarised that the results of the pilot study provide definitive confirmation that the synergy between Industry 4.0 technologies and Lean Six Sigma methodology has already started to evolve and has positive perspectives in the near future. The analysis confirmed that the technology is currently being successfully implemented within Lean Six Sigma methodology.

In the course of the analysis, it was also identified that the most popular implemented technologies within LSS are Robotics, IoT, and Additive Manufacturing, as they currently serve as key enablers for process optimization in industrial companies of the Czech Republic. Furthermore, the research also specified LSS tools, where DMAIC was revealed to be the leader for the implementation of new technologies. As DMAIC is heavily dependent on the statistical component, it makes it reasonable to introduce digital tools to improve this approach.

Overall, the findings reveal that there is a future potential for the conjunction of Lean Six Sigma and Industry 4.0. The results suggest that Industry 4.0 has great potential to increase the speed of optimization via decision making and solutions proposition, as well as to decrease costs related to process speed via Robotics and Simulation. These results of the pilot study successfully set up the baseline for the conjunction, justifying the deeper research that is conducted in the main body of the research.

## 4.3 Analysis of data gathered from companies' representatives

In the following part of the research, the focus is on the detailed analysis of data gathered from companies' representatives during the interview sessions. The participants for the interview were chosen based on the fact of their experience and knowledge of both Lean Six Sigma methodology and Industry 4.0 technologies. The interview respondents included key decision makers such as managers, industrial engineers, and quality engineers, thus those specialists who possess sufficient knowledge of the company's processes and process optimization.

The gathered data was further analyzed qualitatively to answer the research questions. Considering the fact that not all the data can be effectively reduced to statistical numbers, this methodological choice was made deliberately, based on the understanding that the synergy between Lean Six Sigma methodology and Industry 4.0 technologies is a complex phenomenon. Often, the most valuable insights on meanings, barriers, and correlations are found in the case of conversation and in narrative details. Therefore, the qualitative approach was chosen for this part of the research to preserve the richness of data and avoid the loss of relevant, context-dependent information.

The analytical framework for this section was guided by the previous related research steps. Thus, the interview was guided by open questions that were formulated based on the literature review on the conjunction of LSS and I4.0 and a previous pilot study. This ensures that the responses gathered in the course of the data collection expand the existing body of knowledge.

***The meaning of Industry 4.0.***

To provide the necessary background context for the qualitative part, the study first attempts to interpret how the concept of Industry 4.0 is perceived by industrial specialists. The interviews, thus, sought to analyze the understanding of practitioners of the complex notion.

The findings reveal that the term is often interpreted in a fluid manner. As Industry 4.0 is fundamentally related to the term 4$^{th}$ Industrial Revolution, which is conceptualized based on the understanding of the environment characterized by the conjunction of physical and virtual environments, there is no exact list of technologies that constitute the "Industry 4.0", and the term is more related to the overall technological advancement. This lack of a clearly defined set of technologies associated with the term is reflected in the qualitative data. Industrial specialists tend to see the Industry 4.0 term as a broad notion, and for many respondents, the concept is synonymous with the automation of processes and adoption of new technological tools that directly or indirectly lead to the technical revolution. The responses, although having a similar core idea, put emphasis on slightly different aspects and are summarized below:

*A set of technologies that "allow the production to get the data from machines and then use this data further". As for the technologies that are considered to be a part of it, there are "Virtual twins, AI, Power BI, Cloud Computing, robots, and Big Data".*

*"Extensive" term, connected with the "replacement of manual workers", especially with "robotics" and "data analytics". Technologies associated with the term are Simulation, Robotics, Big Data, IoT, and AI.*

*"It's digitalization and automatization of both industrial and non-industrial processes. Reduction of administrative work with people from all sides". Technologies that are used are: Simulation for the "assembly processes, product*

*simulation, digital twin to get to know how the product will behave". Robotics to speed up the process and improve atomization and safety. Virtual reality for preventive maintenance and training. Big Data to decrease waste and predict processes. IoT and sensors to improve automation.*

*"Introduction of modern technologies to industry, which are connected with data collection and assessment. Ideally, this should lead to a self-managing system."*

*"Full process automatization, sensors, PLCs"*

*"Very extensive term in many fields". Automation and digitalization. "All the data from machines where the data from production is used directly without paper. Reduction of manual processes". Technologies that are used in the organization are Simulation, Cloud Computing, Robotics, Big Data, and IoT.*

*"Automatization and robotization in production", "AI for process simplification". "For Big Data, Power BI is used", sensors to monitor and to provide the data set.*

From the gathered responses, it is possible to define a summary of how the industry perceives The Fourth Industrial Revolution. Based on the expert feedback, Industry 4.0 is defined as a comprehensive term for a technological environment aimed at automation, prediction, and waste reduction. In terms of specific technologies associated with the term, practitioners identified a set of dominant technologies, which include Simulation, Big Data, Robotics, AI, and Cloud Computing. Even though these responses align with the technological pillars identified during the literature review, one notable divergence connected with the Cyber-Physical Systems should be mentioned. In the current literature, CPS is considered to be one of the cornerstones of Industry 4.0; however, none of the participants explicitly mentioned CPS. This omission should be considered as a technological absence and a lack of experience with the technology, rather than a terminological gap. The majority of participants lack a thorough understanding of the term, even though they are actively using some of its components, thus connecting physical sensors to the digital clouds. This suggests that although the technology is present in industrial companies of the Czech Republic, the term itself remains popular only in the theoretical field currently.

***Industry 4.0 technologies for LSS projects.***

As the study's focus was mainly on the Lean Six Sigma topic and integration of contemporary technologies within existing industrial optimization processes, an attempt was made to isolate the specific Industry 4.0 technologies implemented specifically for LSS projects. The general idea was not to focus on a general adoption rate, but to identify the set of technologies used for minimizing variation and eliminating waste. However, the analysis revealed that the integration of technologies for Lean Six Sigma could not be viewed in isolation. They are inextricably connected to the technological transformation of the entire enterprise. Consequently, distinguishing between a Lean Six Sigma technology and a company technology posed a particular methodological challenge. In real practice, the boundaries are vague because the sensor installed for production monitoring could simultaneously serve as the sensor for data gathering for the Root Cause Analysis and VSM within the LSS approach. This overlap leads to the interesting convergence in data. The responses on the LSS-specific technologies are the same as those of the general Industry 4.0. This similarity also suggests that for many industrial organizations, LSS has successfully become one of the frameworks in operation processes where the Industry 4.0 tools are implemented.

*"Big Data, and this is more or less it as the only connection" between Industry 4.0 technologies and Lean Six Sigma*

*"This is the part of everyday activity. Many things are set up for that. Simulation for optimization, digital twin". An iPhone application to solve the ergonomics of the working space.*

*"Big Data, data collection", not analytics yet. "Sensors on industrial lines to set up industrial parameters".*

*Big Data, without analysis, "this data was gathered before, but the fact that we are now able to evaluate it within a second has a good effect".*

*"Simulation we use for Lean projects". Power BI for data processing. However, not at the stage of "active usage". "All companies currently just start with the implementation".*

As can be seen from the practitioners' responses, the integration of I4.0 technologies for LSS projects is currently driven by four major technologies, which are mobile devices, simulation, sensors, and Big Data. These technologies were repeatedly identified as the once that have clear results in project environments. This selection is logical, as the use of these technologies could be directly linked to LSS applications for data acquisition with sensors and mobile technologies, and for data processing with simulation and Big Data. At the same time, it should be noted that for other Industry 4.0 technologies, the link to LSS is not that obvious. Respondents found it difficult to come up with examples of how to use other technologies to improve or drive LSS projects. This might suggest that the direct contribution of these technologies to specific LSS improvement is either less visible or less formalized.

To provide a structured visualization of these qualitative data, it was processed with Atlas.ti software dedicated to qualitative analysis. This process extracted the key terms and counted their recurrence, generating the schematic results depicted in Figure 9.


*Figure 9. Industry 4.0 technologies for LSS. Source: own research*

A quantitative review of the data depicted in Figure 9 reveals eight Industry 4.0 technologies that were repeatedly mentioned in the context of LSS projects. The results show that Big Data is currently seen as the most critical enabler for LSS and the most promising tool for enhancing continuous improvement projects. This result could be described by the fact that Big Data serves as a new source of statistical data, thus improving data analytics. Following Big Data, the remaining seven technologies include Artificial Intelligence, Cyber-Physical Systems, Simulation, Sensors, Additive Manufacturing, Digital Twins, and Virtual Reality. This mix could confirm that, despite the priority given to data analytics within the LSS framework, practitioners also explore other possibilities of advanced connectivity to improve process optimization.

***Tasks that are targeted by Industry 4.0 technologies within the scope of Lean Six Sigma projects.***

Following the review of the technological background, the study attempts to define the operational utility of the tools mentioned above. This part of the research aims to identify the major functional tasks that are targeted by Industry 4.0 technologies within the scope of LSS continuous improvement. Understanding of these tasks provides the necessary knowledge on how the new technologies support the process. To answer the question, a coding process was conducted using Atlas.ti software. This analysis revealed that the application of Industry4.0 technologies within industrial organizations is focused on 11 major tasks. The list of tasks is presented below (Figure 10). The numbers adjacent to each code reflect the frequency of the mentions within the analyzed dataset. The results provide a clear picture of what tasks are currently the primary focus for the introduction of digital technologies in the surveyed companies.

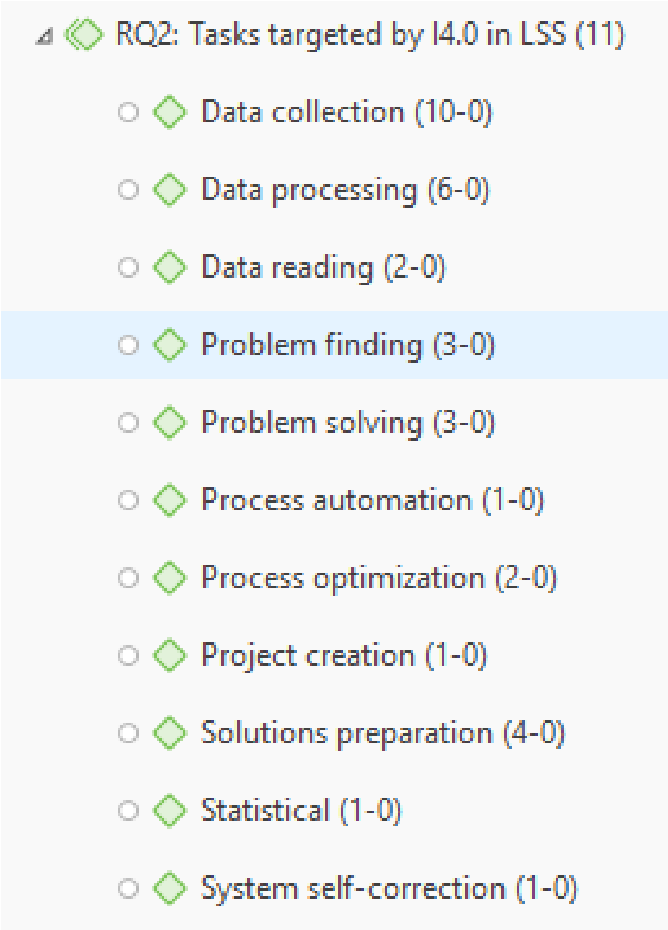


*Figure 10. Tasks targeted by Industry 4.0 technologies. Source: own research*

As presented in Figure 10, specific areas with the priorities where Industry 4.0 technologies provide the most value could be summarized. The data indicates that Data Collection is the leading task targeted by the implementation of Industry 4.0 technologies, as mentioned most often in the feedback from practitioners. This is then followed by Data Processing, thus also confirming the idea that the goal of digitalization is information management. This outcome corresponds logically with the previous research findings, as Big Data was mentioned to be one of the leading technologies for Lean Six Sigma projects. This could be explained by the fact that the high prioritization of Big Data technologies is connected with the need to optimize data-related activities, i.e., gathering large amounts of information and processing this information to valuable outcomes. Thus, Big Data technology and the targeted applications (collection and processing) are perfectly aligned.

As the qualitative research was based on the open-ended questions from industry specialists, some of their comments should also be mentioned to provide the essential evidence for the findings. Specifically, as can be seen, the professionals noted that the major value of Industry 4.0 technologies within the scope of LSS projects lies in the possibilities that are connected with Data gathering, Data processing, and analysis. Thus, the raw data, supporting the analytical results, is presented below, confirming the fact that the industry in the Czech Republic sees digitalization as a critical enabler for the data lifecycle.

*"They were using Lean Six Sigma" which was used for particular purposes, and then it was "suspected, it was in data collection and data reading" the most challenging tasks.*

*"So, we need systems that will collect data," and "people who understand the systems that collect data, experts in that technology".*

*"it goes hand in hand, Industry 4.0 enables collection, LSS teaches how to work with that data and how to use it for better results".*

*"Because the machine talks to us with data, and we are able to use the machine like this, and that is all the information we can collect".*

*For our LSS projects, "we also use sensors on production lines and parameters that we monitor and that we gather information from".*

*"We try to automate data collection and processes; however, currently the human role is important here".*

*"We use it where we can't find the cause of the problem with simple tools and isolate it".*

*"AI, data gathering, etc., so to find a potential problem will be an easy thing".*

*"Big Data analytics can significantly influence Lean Six Sigma as it has the potential to process data and give quicker solutions".*

*"We will be able to target more projects, have more detailed analysis, and come up with faster solutions".*

As it could be noted from the respondents' answers, the most significant potential for value creation is currently seen in the domain of data processing.

Considering the development of the technologies and the rapid progress in data analysis, this finding is both logical and expected. Moreover, looking further ahead, the findings indicate a shift towards intelligent automation. There is a strong expectation that Artificial Intelligence will soon be available to propose solutions for the issues identified during analysis. However, the question of data security, together with some other barriers, remains an important topic.

***Barriers connected with the introduction of Industry 4.0 technologies.***

Another important idea targeted in the study is to summarize what are the major barriers connected with the introduction of Industry 4.0 in Czech companies. As Lean Six Sigma processes can be influenced only by the technologies that companies are willing to use, it is important to understand what might block companies from introducing these technologies. A look at the practitioners' answers here provides the data for the analysis of the topic:

*"People, people's reluctance to cooperate" ... "now there are few people who want to work, the problem is finding people who are able to work with it - visionary forward". "Investment - whether it pays off or not".*

*"Worry about whether it will work or not. The most important thing is that if the process doesn't worth anything, there's no need to digitalize it".*

*"It is mainly the few people who understand it, to find enthusiasm in the company for understanding, if the management realizes the necessity, to have a specialist for it". And to "teach people" who are not very good at it to work with it. "None of these machines are autonomous", you need to assign people. "People are afraid of losing their jobs or getting extra tasks".*

*"Staff preparation, new tools, this is the question of training".*

*"From a practical viewpoint, automation is fine; however, more service is required" to support the running. "It is good to have a robot, but it is necessary partly to have services to set its function". All the technologies require "training. Further is data protection and AI – "every company wants to be safe and not everything can be put there".*

*"The biggest problem is investment and people who can understand it. Lack of qualified people." Some tasks cannot currently be done by machines as a higher level of standardization is needed.*

The comments provided above give evidence that the major barrier to process digitalization is connected with human factors. This barrier could be divided into two major groups: motivation and expertise. As for the motivation, it could be said that despite the fact that the term Industry 4.0 is no longer a novel concept, there is a consistent fear among the workers and a low understanding of its practical applications. This brings reluctance of workers to implement new technologies as they are worried about their adaptability to new processes and the potential that their work could be overtaken by technologies. At the same time, a significant deficit of the required knowledge can be seen on the market, as there are not enough experts who could use both the industrial processes and new technologies, which creates a bottleneck that slows down the meaningful integration.

The systematic coding analysis, as depicted in Figure 10, depicts the same ideas that the majority of barriers are overwhelmingly related to the human aspect. An interesting finding from the graph might be connected with the specific position of training. Although training is listed as a barrier, as it is inextricably connected with investments in both time and costs, it could also serve as a partial solution to overcome other barriers. By accepting the costs of training, companies can directly target other issues of employees' fear of extra tasks and fear of technology, thus also reducing the reluctance and equipping the workforce with the necessary knowledge to implement the complexities and digitalized LSS projects.

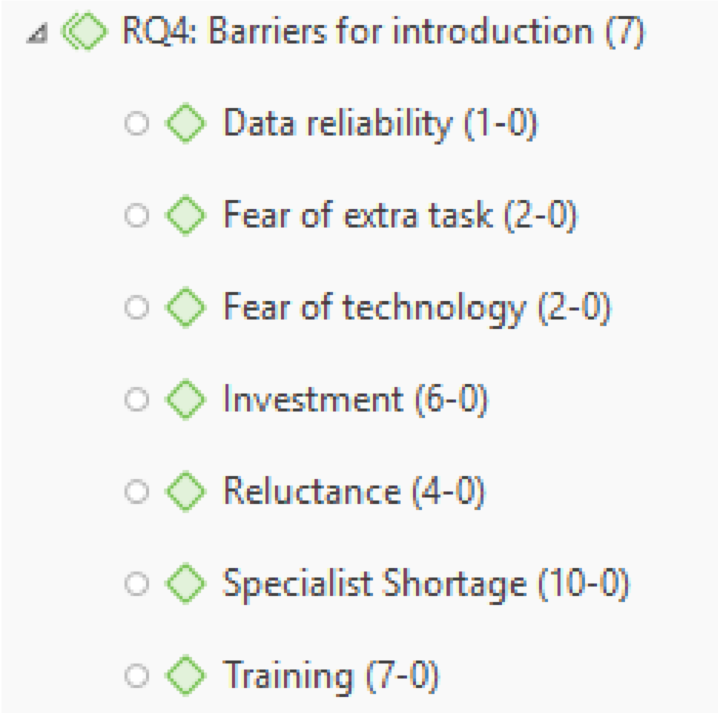


*Figure 11. Barriers to the introduction of Industry 4.0 to LSS. Source: own research*

To sum everything up, it could be seen that all the barriers could be divided into 4 main categories, which are, although related, represent slightly different domains. These four categories are Motivation-related, which include fear of extra tasks, fear of technologies, and reluctance; Expertise-related, which includes specialist shortage and training; Investments-related, and Data-related, which includes data reliability and data security. These four categories provide the idea that the berries are not purely technological or human, but they represent a mixture of several fields.

***Lean Six Sigma and Industry 4.0 are a beneficial conjunction.***

One of the most relevant questions of this study is how practitioners see the conjunction of Industry 4.0 and Lean Six Sigma. Whether Lean Six Sigma should serve as a prerequisite for the introduction of Industry 4.0 technologies or whether Industry 4.0 technologies allow easier usage of Lean Six Sigma tools, thus leading to the popularization of this methodology. This distinction is important as it helps to understand whether the concepts of LSS and I4.0 are viewed separately or as an integrated, simultaneous strategy for operational improvement.

*In the future, Industry 4.0 "can help to look for anomalies in data for LSS projects".*

*The conjunction is seen positively. Especially in the area of data collection, it goes hand in hand. Industry 4.0 enables collection, and LSS teaches how to work with that data and how to use it for better results.*

*"Without having any Industry 4.0 implemented for Lean Six Sigma, it is necessary to come up with something for data gathering".*

*"Lean will always stay". Maybe Industry 4.0 will take over something from Six Sigma". "I see Lean in the future, Six Sigma may be fully digitalized in the future".*

*The roof of the hut is "nothing better than digitalization, but the foundation is LSS".*

*The potential of LSS is "to evaluate the implementation of new technologies".*

*"Most manual operations will be saved by AI, collection, analysis, etc., so that a potential problem may eventually become easily analyzed".*

*The perfect scenario is first optimization and then technologies. "If we implement technologies in a mess, it won't be good". "It is important to set it in a good way, and then it will start to function".*

*Lean can "definitely" work as a foundation for the implementation of Industry 4.0 technologies. "And in 5-10 years it will be more integrated, "especially with increasing work price".*

According to the qualitative research performed based on the data mentioned above, and also the qualitative assessment in Atlas.ti software, the conjunction of Industry 4,0 technologies and LSS tools is viewed overwhelmingly as a beneficial conjunction. Every practitioner who participated in the study noted that when aligned in a proper way, LSS and I4.0 mutually enhance each other. At the same time, the data suggests that the order of implementation is important. A visible pattern in the responses (4 out of 7 interviews) emphasizes that first, LSS tools should be implemented, then I4.0 technologies. The experts point out that the role of LSS could be to prepare the environment with LSS approach, thus analyzing workflows and reducing variability, for the introduction of advanced technologies in order to avoid unnecessary spending. The data in Figure 12 also indicates, that when LSS is used to clean processes, and Industry 4.0 is used to automate it, the result is a highly effective process.

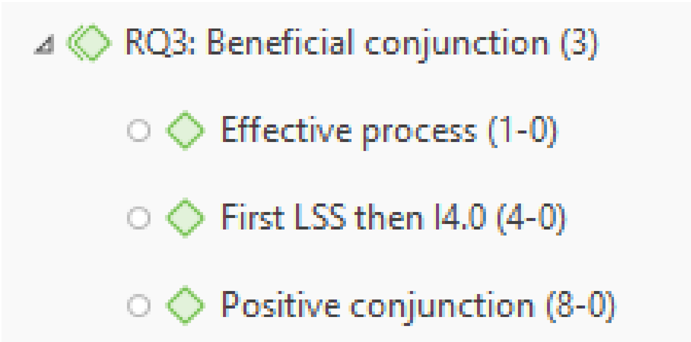


*Figure 12. Is Industry 4.0 and LSS a beneficial conjunction? Source: own research*

Considering the aforementioned, it can be said that LSS has a great potential to assess the processes before the implementation of new technologies; however, at the same time, Industry 4.0 technologies can significantly improve and speed up the LSS project. From a strategic point, LSS is validated as a critical basic step due to its ability to assess processes and eliminate wastes. This makes LSS an ideal prerequisite for protecting the ROI of digital investments. At the same time, Industry 4.0 starts by resolving the traditional limitations of LSS, which are manual data collection and slow analysis. With the implementation of real-time visibility and Big Data collection, technologies significantly speed up project timelines. Therefore, the combination is viewed as mutually beneficial.

To conclude the qualitative part of the research, the textual data were processed to generate a Word Cloud that depicts the most re-occurring themes in the expert interviews. This visualization serves as a fingerprint of the industry's current mindset. The logic of the Word Cloud is ordinary, meaning that the bigger the font size, the higher the frequency of this term's usage. While Lean Six Sigma and Industry 4.0 are expected to appear as the anchors of the topic, the surrounding offers a deeper insight. Thus, the terms "People", "Organization", and "Process" appear with significant weight. This distribution indicates that the respondents consider Industry 4.0 and Lean Six Sigma within the context of the business environment, which includes other constituents. The result also confirms that the conjunction is inextricably connected with the management of people and processes, rather than a separate technological standard.

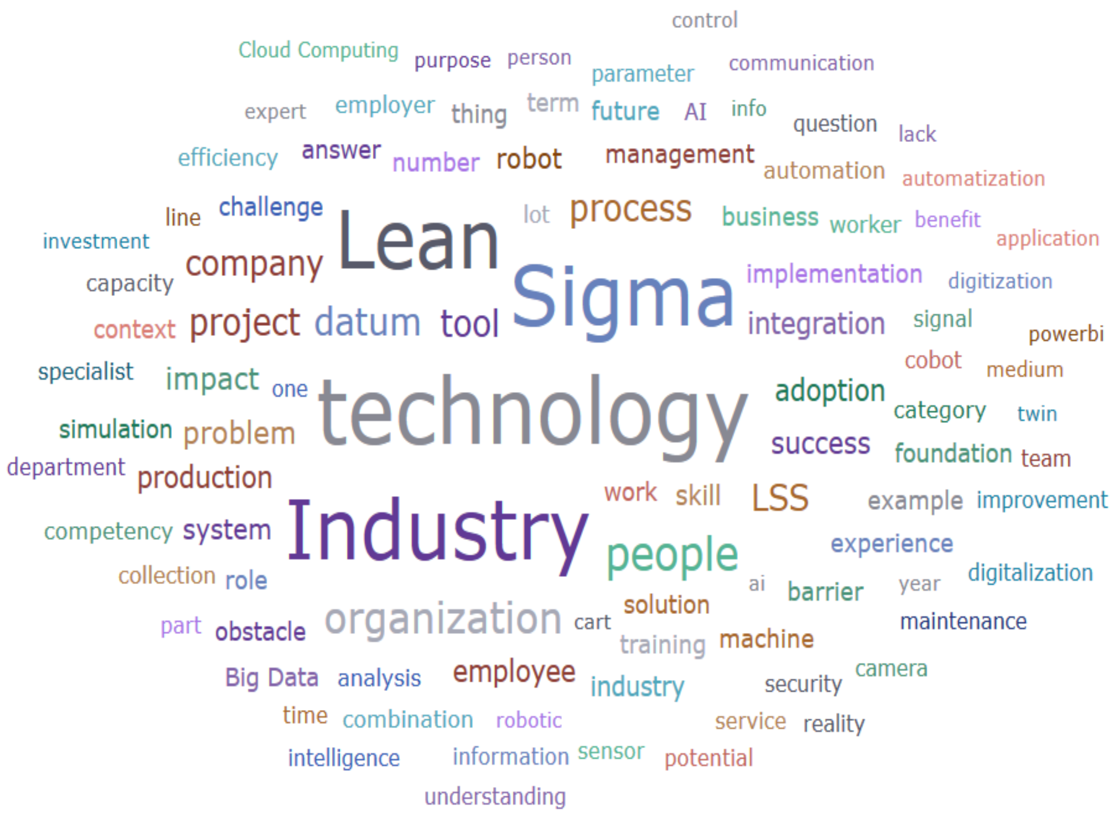


*Figure 13. Word cloud. Source: own research*

***Code density and co-occurrence analysis***

As a final step of the qualitative part of the analysis, the textual data were subjected to the Code-document Co-occurrence analysis using the advanced computational capabilities of the Atlas.ti software. This methodological step was important to provide the overview beyond the simple frequency count performed above, where it is analyzed how often a word or a phrase is said, to investigate the relational density of the concepts, which are in this case research questions within specific interviews. This technique allows for a better view of the data distribution, highlighting which research topics appeared most consistently across different interviews. Rather than viewing the questions in isolation, the analysis puts them within the context of specific participants, thus providing insight on where the discussion was the most intense. The visual representation can be seen in Figure 14, which also provides a clear picture of the saturation level of the research topic.

| | 1: Interview_... 3 | 2: Interview_... 25 | 3: Interview_... 18 | 4: Interview_... 16 | 5: Interview_... 25 | 6: Interview_... 11 | 7: Interview_... 7 | Totals |
|---|---|---|---|---|---|---|---|---|
| RQ1: In... 8 21 | | 4 | 4 | 7 | 4 | 1 | 1 | 21 |
| RQ2: T... 11 33 | | 9 | 7 | 4 | 10 | 2 | 1 | 33 |
| RQ3: B... 3 12 | 1 | 1 | 2 | 2 | 3 | 1 | 2 | 12 |
| RQ4: B... 7 32 | 2 | 10 | 4 | 2 | 7 | 4 | 3 | 32 |
| Totals | 3 | 24 | 17 | 15 | 24 | 8 | 7 | 98 |

*Figure 14. Analysis of code document co-occurrence. Source: own research*

The quantitative distribution of code provides insight into the richness of the gathered data. From this analysis, it could be seen that Interviews 2 and 5 serve as the primary source of detailed information, characterized by the highest number of codes. This is explained either by the fact that these respondents possessed a deeper practical experience with the topic or a greater willingness for detailed explanation. On the opposite side, Interview 1 has the lowest code count, reflecting a more reserved communication style. This variation also defines that the data was gathered from different perspectives, ranging from highly technical, detailed viewpoints to more simplified overviews. However, the lower density of certain interviews did not compromise the study's validity. It is important to note also that the data demonstrates that the research has reached the point of saturation. The re-occurring patterns observed across the high-density interviews were aligned with the supporting interviews, ensuring that no further data collection was necessary to construct a comprehensive answer to research questions.

## 4.4 Analysis of data from industrial companies

Following the qualitative part of the research, the study proceeds to the quantitative part of the analysis. To empirically measure the impact of Industry 4.0 technologies on Lean Six Sigma project success, a research questionnaire was developed and distributed among the industry professionals in the Czech Republic. The questionnaire instrument was designed to gather data, allowing for the generalization of the findings to the larger scope in comparison with the individual interviews. The gathered data was subject to statistical assessment with the purpose of getting a clear picture with concrete numerical evidence that addresses the major research objectives. The basis for the analysis is on the test of validity of the proposed hypothesis. For all statistical tests performed and described further in the study, the standard significance level α is set at 0.05. This relates to the confidence level of 95% for the results. The major rule that was applied is as follows: if the calculated p-value is less than the significance level, the null hypothesis is rejected, proving a statistically significant relationship between the variables. Otherwise, when the p-value is higher than the significance level, the null hypothesis cannot be rejected and thus is retained. Further in the research, the statistical relationship is analyzed for each set of variables.

#### 4.4.1 Association between Lean Six Sigma project success (from the point of view of time, budget and efficiency) and company's characteristics, such as company's size, company's industry, company's experience in Lean Six Sigma, certification in Lean Six Sigma, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology, active trainings on Lean Six Sigma, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory.

Following the described research plan, an attempt is made to evaluate the environment in which the LSS project exists, with the biggest success. The objective here is to determine if the company's characteristics could act as a predictor for LSS project success. In the scope of this analysis, a set of organizational characteristics is tested, including company's size, company's industry, company's experience in LSS, certification in LSS, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology, active training on LSS, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory.

The evaluation of a project's success is based on a standard project management (PM) theory, where each project has 3 major constraints, that are budget, scope, and time. Thus, the results are divided into three logical parts that describe success from the perspectives of project Budget, project Efficiency and project Time. The measurement methodology is based on the comparison of the planned targets against the actual outcomes to determine if the company's characteristics influence the project's ability to respond to the initial targets.

***Lean Six Sigma project success from the budget point of view***

The quantitative analysis begins with the evaluation of the impact of the company's characteristics on Budget success, defined for this study as the project's ability to adhere to the planned costs. As the dependent variable in this part is ordinal, non-parametric statistical techniques were used to maximize the accuracy of data analysis. Thus, to quantify the strength of association, Spearman's rho correlation analysis was used, and to evaluate differences between groups and the strength of the combination, Mann-Whitney U and Kruskal-Wallis tests were conducted. On this basis, hypothesis testing was performed to determine if a significant relationship exists. The fundamental hypothesis established for this section is as follows:

*$H_0$(1) None of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a budget perspective.*

*$H_A$(1) At least one of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory influence project success from a budget perspective.*

The first part of the analysis is shown in Table 7. As it could be seen form the table, only a weak association can be seen between LSS project success from the budget point of view and project characteristics that were analyzed in this part, such as experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles and active usage of LSS in the company, as well as the active training participations for LSS of the company, attempt to introduce Industry 4.0 technologies and attempt to create Smart Factory. Moreover, the same characteristics showed that there is no statistical significance between the two variables mentioned above. This lack of significance implies that a company's structural and experiential maturity has no measurable impact on the budget indicators of its Lean Six Sigma projects in this sample.

Table 7. Correlation analysis of the LSS project success based on the budget. Source: own research

| | | | **Variance in plan vs reality in budget** |
|---|---|---|---|
| Spearman's rho | Experience with LSS | Correlation Coefficient | -,027 |
| | | Sig. (2-tailed) | ,836 |
| | | N | 62 |
| | Experience with I4.0 | Correlation Coefficient | -,096 |
| | | Sig. (2-tailed) | ,456 |
| | | N | 62 |
| | LSS certificate | Correlation Coefficient | -,132 |
| | | Sig. (2-tailed) | ,306 |
| | | N | 62 |
| | Kazen implemented | Correlation Coefficient | ,086 |
| | | Sig. (2-tailed) | ,508 |
| | | N | 62 |
| | Programs and workshops for Lean | Correlation Coefficient | ,128 |
| | | Sig. (2-tailed) | ,323 |
| | | N | 62 |
| | Attempt to introduce new technologies | Correlation Coefficient | -,224 |
| | | Sig. (2-tailed) | ,080 |
| | | N | 62 |
| | Active usage of Lean Six Sigma | Correlation Coefficient | ,202 |
| | | Sig. (2-tailed) | ,116 |
| | | N | 62 |
| | Attempt to create a Smart Factory | Correlation Coefficient | -,138 |
| | | Sig. (2-tailed) | ,283 |
| | | N | 62 |

To provide a fuller picture, other parameters were also examined within the scope of the research, which include company size and the company's industry. For the company size, the Mann-Whitney U test was used, as categories such as small and SME were set up for these x-variables. The results of the analysis are depicted in Figure 15. According to the results, it could be seen that the statistical significance is low as the p-value is much higher than 0.05. This would lead us to the conclusion that there is no evidence that the Lean Six Sigma project's success from the budget point of view is different between the SMEs and large-scale companies' size groups.

**Hypothesis Test Summary**

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality in budget is the same across categories of Company size. | Independent-Samples Mann-Whitney U Test | ,393 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 15. Analysis of the company's size influence on LSS project success based on the budget. Source: own research*

In the final part of this section, the analysis investigates the association between industry sector and project success based on the budget. For the purpose of this evaluation, all the participating companies were divided into 12 groups based on their primary field of operation. To test the significance across this number of groups, the Kruskal-Wallis test was applied. This method was chosen because the predictor of this part, which is industry, is nominal in nature, while the response (Budget success) is ordinal. Thus, a valid statistical basis was gathered to compare the performance across different sectors.

## Hypothesis Test Summary

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality in budget is the same across categories of Company profile. | Independent-Samples Kruskal-Wallis Test | ,329 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 16. Analysis of industry influence on LSS project success based on budget. Source: own research*

According to the results of the Kruskal-Wallis test, depicted in Figure 16, it could be observed that the p-value is significantly higher than the standard significance level of 0.05. Based on these metrics, the analysis concludes that there is no statistically significant relationship in project success from the budget perspective across different industry sectors.

In conclusion, the quantitative assessment of this first part of the project's success from the budget perspective reveals a lack of association across all tests. The statistical analysis thus confirms that neither company's internal characteristics nor its industrial sector proved to be significant predictors for the LSS project's success from the budget point of view. As no calculated p-value met the significance level of 0.05, the research concludes that no statistical relationship exists. Thus, the null hypothesis associated with the LSS project's success from the budget perspective is retained, establishing that general organizational attributes do not guarantee the financial success of LSS projects in this dataset.

### *Lean Six Sigma project success from the time point of view*

The second part of the quantitative analysis is targeted to assess the metric of the project timeline. In a fast-moving industrial environment, the ability to deliver the LSS project results on time is as critical as delivering them within budget. Thus, using the established statistical framework from the previous step, the research analyzes the relationship between a company's characteristics and their ability to influence project success from a time perspective. The analysis seeks to determine if factors like experience with Lean Six Sigma, experience with Industry 4.0, Lean Six Sigma certificates, implemented Kaizen principles, active usage of Lean Six Sigma in the company, active training for Lean Six Sigma, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory correlate with faster or more predictable project execution form the time perspective. The hypothesis for this part is formulated as follows:

*$H_0(2)$ None of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, influences project success from a time perspective.*

*$H_A(2)$ At least one of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, influences project success from a time perspective.*

To evaluate the time perspective dimension of LSS project success, Spearman's correlation analysis was also used for this dataset. The results of the analysis are depicted in Table 8, where it can be seen that the results are largely similar to the budget constraint of the research, exhibiting small correlation coefficients and statistically non-significant p-values regarding the project timelines. However, an interesting miscellaneous was initially observed. The analysis identifies a potential positive association between LSS project success from a time perspective and the implementation of Kaizen principles in the company. This relationship has a Spearman's rho ($\rho$) of 0.238 and a p-value of 0.026. With the significance level of $\alpha = 0.05$, the results indicate a statistically significant finding, suggesting that a stronger Kaizen culture is associated with better adherence to the initial timing plan within LSS projects. At the same time, given that the multiple hypothesis tests were conducted simultaneously, which is in this case 8 distinct tests, the risk of getting a so-called "false positive" or Type I error should also be considered in this situation. To maintain the statistical validity of the results, a Bonferroni correction with the adjusted threshold was applied in the given case. With the initial significance level of $\alpha = 0.05$ and the number of tests applied = 8, the adjusted threshold became $\alpha_{adj} = 0.05/8 = 0.00625$. In this environment, since the p-value from the analysis of 0.026 is higher than this stricter threshold, i.e., $0.026 > 0.00625$, the relationship fails to prove its statistical significance. Thus, the initial result of the analysis, where Kaizen has a statistical association with the LSS project success from the time perspective, should be interpreted as a statistical artifact rather than a definitive predictor.

Table 8. Correlation analysis of the LSS project success based on time. Source: own research

| | | | Variance in plan vs reality on time |
|---|---|---|---|
| Spearman's rho | Experience with LSS | Correlation Coefficient | -,076 |
| | | Sig. (2-tailed) | ,557 |
| | | N | 62 |
| | Experience with I4.0 | Correlation Coefficient | -,142 |
| | | Sig. (2-tailed) | ,271 |
| | | N | 62 |
| | LSS certificate | Correlation Coefficient | -,045 |
| | | Sig. (2-tailed) | ,727 |
| | | N | 62 |
| | Kazen implemented | Correlation Coefficient | ,283* |
| | | Sig. (2-tailed) | ,026 |
| | | N | 62 |
| | Programs and workshops for Lean | Correlation Coefficient | ,188 |
| | | Sig. (2-tailed) | ,143 |
| | | N | 62 |
| | Active usage of Lean Six Sigma | Correlation Coefficient | ,119 |
| | | Sig. (2-tailed) | ,357 |
| | | N | 62 |
| | Attempt to introduce new technologies | Correlation Coefficient | -,050 |
| | | Sig. (2-tailed) | ,700 |
| | | N | 62 |
| | Attempt to create a Smart Factory | Correlation Coefficient | ,057 |
| | | Sig. (2-tailed) | ,660 |
| | | N | 62 |

To further investigate the influence of the company's characteristics and their association with the LSS project success from the time perspective, the influence of company size was examined using the Mann-Whitney U test. Same as in the case with the budget perspective previously, this non-parametric method compares the distribution of LSS timeline project success between the two groups that are large enterprises and SMEs. The results of the analysis are depicted in Figure 17. Here, we can observe that the statistical output of the p-value in this case is 0.972, which is exceptionally close to the maximum value of 1.0. This result is obviously far above the significance level of 0.05, and thus, it provides strong evidence that there is no association between the company size and LSS project success from a time perspective. Moreover, such a high p-value also indicates that the performance between 2 groups is nearly the same. Therefore, there is no statistically significant difference in the LSS timeline project success based on the organizational size, which means that whether the company is a large enterprise or an SME, this cannot influence the ability to meet project deadlines.

**Hypothesis Test Summary**

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality on time is the same across categories of Company size. | Independent-Samples Mann-Whitney U Test | ,927 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 17. Analysis of the company's size influence on LSS project success from a time perspective. Source: own research*

To proceed with the analysis, the influence of the industry sector on the LSS project success from a time perspective was assessed using the Kruskal-Wallis test. The results of this analysis could be seen in Figure 18. Considering the calculated p-value of 0.390, the results here show no statistical evidence that there is a relationship between the company's industry of operation and the LSS project's ability to successfully meet the planned deadlines. The p-value is high above the significance level of $\alpha = 0.05$, confirming that the performance and the results in this relation are similar across different industrial groups included in the survey.

**Hypothesis Test Summary**

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality on time is the same across categories of Company profile. | Independent-Samples Kruskal-Wallis Test | ,390 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 18. Analysis of industry influence on LSS project success from a time perspective. Source: own research*

Summarizing the empirical evidence gathered in this part of the research, regarding the LSS project from the time perspective, a clear conclusion could be made: the study found no statistical evidence to support the hypothesis that a company's characteristics serve as a predictor for the LSS project success from the time point of view. A systematic review of the independent variable, including experience with LSS, experience with Industry 4.0, LSS certificates, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, revealed no significant association in the sample. It should be noted, though, that the implemented Kaizen principles variable initially suggested a positive correlation, but it failed to prove that there is a significance with Bonferroni correction for multiple comparisons, classifying the initial findings as a statistical artifact rather than an existing trend. Moreover, further analysis of other variables showed similar results; neither company size nor industry sector proved to be the factor that could influence or forecast the result. Thus, based on the complete absence of statistically significant p-values, the null hypothesis is retained. This confirms that, within the studied population, the ability to deliver the LSS project results on time is independent of the company's characteristics.

***Lean Six Sigma project success from the efficiency perspective***

The final part of this quantitative section assessed Lean Six Sigma project success from the perspective of efficiency. This variable serves as the third pillar of performance analysis, and thus it adds important input to the data already gathered in the previous parts, where the Budget and Time perspectives were examined. In the survey instrument, LSS project efficiency was on a predefined ordinal scale, allowing the respondents to rate the outcome of their LSS project initiatives. Considering the ordinal nature of the dependent variable (y-variable), the methodological approach used in this part remains similar to the previous two parts. In the study, the non-parametric statistical tests are used to ensure the validity as follows: Spearman's correlation to assess associations with ordinal predictors, Mann-Whitney U Test to conduct two-group comparison of the company size, and Kruskal-Wallis H Test to analyze comparison across a larger number of categories, that is, 12 industry sectors in the given case. To empirically assess what are the factors that could influence LSS project success from the efficiency perspective, hypothesis testing was done. The specific set of hypotheses guiding this part of the analysis is as follows:

*$H_0(3)$ None of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, influences project success from an efficiency perspective.*

*$H_A(3)$ At least one of the company's characteristics, such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, influences project success from an efficiency perspective.*

The results for Spearman's analysis are depicted in Table 9, indicating that the analysis for the LSS project success from the efficiency perspective shows similar trends as in previous parts of this section related to Time and Budget. The statistical assessment shows that the efficiency of the project is not dependent on the company's characteristics applied in this part. None of the examined variables, including experience with LSS, experience with Industry 4.0, LSS certificates, Kaizen principles implemented in the company, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, proved to be associated with the Efficiency outcomes. All the coefficients remained small and non-significant across the sample. This suggests that these characteristics, although being a part of the company's characteristics, could not directly influence the project's success from the efficiency point of view.

Table 9. Correlation analysis of the LSS project success based on efficiency. Source: own research

| | | | **Variance in plan vs reality in efficiency** |
|---|---|---|---|
| Spearman's rho | Experience with LSS | Correlation Coefficient | ,088 |
| | | Sig. (2-tailed) | ,497 |
| | | N | 62 |
| | Experience with I4.0 | Correlation Coefficient | ,064 |
| | | Sig. (2-tailed) | ,623 |
| | | N | 62 |
| | LSS certificate | Correlation Coefficient | ,015 |
| | | Sig. (2-tailed) | ,909 |
| | | N | 62 |
| | Kazen implemented | Correlation Coefficient | ,062 |
| | | Sig. (2-tailed) | ,634 |
| | | N | 62 |
| | Programs and workshops for Lean | Correlation Coefficient | ,016 |
| | | Sig. (2-tailed) | ,905 |
| | | N | 62 |
| | Active usage of Lean Six Sigma | Correlation Coefficient | ,065 |
| | | Sig. (2-tailed) | ,618 |
| | | N | 62 |
| | Attempt to introduce new technologies | Correlation Coefficient | ,183 |
| | | Sig. (2-tailed) | ,154 |
| | | N | 62 |
| | Attempt to create a Smart Factory | Correlation Coefficient | ,042 |
| | | Sig. (2-tailed) | ,746 |
| | | N | 62 |

In order to investigate the relationships between the organizational size and the efficiency outcome of the LSS project, a Mann-Whitney U test was conducted to compare large enterprises against SME, similarly as it was done in the previous steps for Budget and Time. The results of the comparative analysis are shown in Figure 19. The test has a p-value of 0.0673, thus it should be noted that even though this value approaches the threshold of significance closely that he previously analyzed variables of Time and Budget, it still remains above the established significance level of $\alpha = 0.05$. Thus, according to the study's statistical parameters, the result is not statistically significant. Therefore, no evidence was found to suggest that the size of the company could determine the LSS project's success from an efficiency perspective.

**Hypothesis Test Summary**

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality in efficiency is the same across categories of Company size. | Independent-Samples Mann-Whitney U Test | ,673 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 19. Analysis of the company's size influence on LSS project success from an efficiency perspective. Source: own research*

Finally, the Kruskal-Wallis test was applied to determine whether the industrial sector of the company could serve as a predictor for the LSS project efficiency. The goal was to assess whether specific industries achieve higher efficiency ratings than others. As with the previous variables, this analysis revealed that there is no significant association. The calculated p-value of 0.334 is much higher than the significance level of $\alpha = 0.05$, thus confirming that the industry sector does not influence the LSS project success from the efficiency perspective. It should be noted as well that the findings are aligned with the findings from previous steps for Time and Budget, thus suggesting that the LSS project's success is not associated with the industrial sector. The challenges and successes of LSS projects seem to be more universal than any single industry-specific.

**Hypothesis Test Summary**

| | Null Hypothesis | Test | Sig. | Decision |
|---|---|---|---|---|
| 1 | The distribution of Variance in plan vs reality in efficiency is the same across categories of Company profile. | Independent-Samples Kruskal-Wallis Test | ,344 | Retain the null hypothesis. |

Asymptotic significances are displayed. The significance level is ,05.

*Figure 20. Analysis of industry influence on LSS project success from an efficiency perspective. Source: own research*

To conclude this part of the analysis, it should be noted that no statistical evidence was found confirming that there is an association between the company's characteristics and LSS project success from the efficiency perspective. The results of the Spearman correlation were small and non-significant, and group comparison showed no difference by company size and no difference across industry categories. Consequently, the null hypothesis is retained for this part. The data suggests that the LSS project's efficiency is a universal challenge, and it is not mitigated by the company's characteristics.

In conclusion, summarizing the comprehensive quantitative analysis, a particular pattern of independence between the tested variables emerges. Across all three pillars that were assessed in this part of the research from the success point of view, i.e. Budget, Time and Efficiency, the research found no empirical evidence to suggest that company's characteristics such as company's size, company's industry, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory, serve as a predictor for Lean Six Sigma project's success. Based on the gathered dataset from 62 industrial companies operating in the Czech Republic, the statistical testing revealed a unified lack of significance. Whether examining internal company characteristics such as LSS experience and training, or external characteristics such as company size and industry sector, the result constantly stayed below the level of statistical significance of $\alpha = 0.05$. Therefore, the null hypothesis is retained for all tested relationships. These findings suggest that the company's characteristics are not the differentiating factor for LSS project success with this sample.

### 4.4.2 Association between Lean Six Sigma project success (from the point of view of time, budget, and efficiency) and the project's characteristics, such as project duration, project budget, and the number of the project's participants.

Following the assessment of the company's characteristics' influence on the LSS project's success, the research proceeds with a shift of its analytical focus to the micro-level determinants of the project's success. Therefore, this section is devoted to the analysis of the association between Lean Six Sigma project success from the Budget, Time, and Efficiency perspectives and the specific characteristics of the LSS projects themselves. Considering that the previous section examined the environment in which LSS projects operate and whether this environment is associated with the LSS project's success, this section concentrates more on three key independent variables, that were chosen for the analysis: Project duration, i.e. the timeline allocated for the project; Project Budget, i.e. the finances accounted for the project; and Number of participant, i.e. the size of the active participants involved in the project team activities. The objective of this part is, thus, to determine if the timeline, costs, or team of a LSS project could act as a predictor for the LSS project's success in terms of Time, Budget, and Efficiency.

To empirically examine the above-mentioned combinations and to validate the relationships, the overall hypothesis was formulated as follows:

*$H_0(4)$ None of the project's characteristics, such as project duration, project budget, and number of project participants, influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_A(4)$ At least one of the project's characteristics, such as project duration, project budget, and number of project participants, influences LSS project success (from a budget, time, and efficiency perspective).*

The statistical methodology of this section was determined by the specific properties of the dataset, namely the nature of the variables and the sample size. In this dataset, the dependent variable (y) is the LSS project's success from the Budget, Time, and Efficiency point of view, and this variable was measured using the 5-point Likert scale; the variable is classified as ordinal data. The independent variables (x) for this part of the research are project duration, project budget, and the project's number of participants, and here the variables were not measured as continuous raw numbers but were divided into 5 separate categories, i.e., specific time blocks or budget constraints, thus this group of variables belongs to the categorical dataset. Considering the combination of ordinal outcomes and categorical predictors, and a moderate sample size of N = 62, parametric requirements were not met. Thus, the non-parametric framework, as a Kruskal-Wallis Test, was performed as the most suitable method for the given dataset. This test allows us to determine if the comparison of five categories is associated with the LSS project's success. The results in the form of p-value gathered in the scope of the analysis for all variables are synthesized in Table 10.

Table 10. P-values for LSS Project success and Project characteristics associations. Source: own research

| | **Variance in the budget** | **Variance in time** | **Variance in efficiency** |
|---|---|---|---|
| Project budget | 0,286 | 0,693 | 0,840 |
| Project duration | 0.403 | 0,658 | 0,695 |
| Project participants | 0,052 | 0,220 | 0,470 |

A review of p-values in Table 10 reveals that there is a consistent lack of statistical significance across the majority of the tested combinations. However, it should be noted that one specific relationship is exceptionally close to the set level of statistical significance. Thus, the association between the Number of Project Participants and the LSS project's variance in Budget has a calculated p-value of 0.052. While the result is close to the significance threshold, it technically exceeds the established level of $\alpha = 0.05$. Consequently, despite the strong indication of a potential trend, the result is classified as statistically non-significant. For the rest of the variables, i.e., Project budget and Project Duration, the p-values are significantly high, ranging from a p-value of 0.220 to 0.840. This confirms that neither the money allocated for the project nor the timeline serves as a valid predictor for the LSS project's success in terms of Budget, Time, and Efficiency.

To sum up, 9 Kruskal-Wallis tests were performed to examine the influence of the project characteristics on the LSS project success from a budget, time, and efficiency perspective. Across all tests, no statistically significant associations were found, as all of the p-values were higher than the target value of 0.05. The lowest p-value observed in the set is between LSS project Success from the budget perspective and the number of project participants, which, although approaching significance, has not met the required level of 0.05.

To conclude this section, the investigation into the Project's Characteristics reveals that Time, Budget, or number of participants of any given LSS project is not a determinant of the project outcome. The statistical testing performed in this part found no evidence to support the claim that the budget allocated to the project, longer timelines, and bigger LSS project teams could be associated with higher or lower LSS project success rates from a budget, time, or efficiency perspective. The p-values exceeded the significance level, indicating that the LSS project's success is distributed independently of these variables. Therefore, the overall null hypothesis $H_0(4)$ None of the project's characteristics, such as project duration, project budget, and number of project participants, influences LSS project success (from a budget, time, and efficiency perspective) was not rejected in the given conditions.

### 4.4.3 The extent to which utilization (usage) of Industry 4.0 technologies is related to the Lean Six Sigma project success outcome.

Since the evaluation of the organizational context (company's characteristics) and operational context (project's characteristics) has been completed in the previous sections, this section of the research addresses the primary analytical objective of the research by assessing the impact of Industry 4.0 technologies on the Lean Six Sigma project's success. This section represents the core of the research as it explores the potential synergy between the I4.0 digital transformation with its advanced tools and process improvement methodology, namely Lean Six Sigma, in the given context. To define the extent of the research properly, the analysis was structured to consist of two complementary parts based on the volume effect and specific technology effect. In the first phase of the given section an attempt is made to isolate individual technologies related to the I4.0 environment, such as Dig Data, Robotics, Simulation, Augmented reality, Cloud Computing, the Internet of Things, and Artificial Intelligence, and to determine if specific technologies could possess a stronger influence on the LSS project success from the Budget, Time and Efficiency perspective than the others. The second part, thus, investigates whether the number of I4.0 technologies introduced in the company could be associated with the LSS project's success from the same perspective it was measured in the previous sections, i.e., in terms of Budget, Time, and Efficiency. By separating the volume view from the type of technology view, the research seeks to provide a thorough view of how the combination of I4.0 technologies and LSS methodology works in practice.

Following this structured approach, the research has the following hypotheses to test the relationship between technological adoption and LSS project performance:

*$H_0$(5) None of the Industry 4.0 technologies influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_A$(5) At least one of the Industry 4.0 technologies influences LSS project success (from a budget, time, and efficiency perspective).*

*$H_0$(6) There is no correlation between the number of Industry 4.0 technologies and project success.*

*$H_A$(6) There is a correlation between the number of Industry 4.0 technologies and project success.*

***Specific Industry 4.0 technologies' association with the Lean Six Sigma project's success***

To empirically estimate the association between the application of specific Industry 4.0 technologies and Lean Six Sigma project success, a Spearman's correlation test was performed. This non-parametric method was selected to assess the strength and direction of the monotonic association of variables. The testing procedure involved cross-referencing each separate technology against the three basic scopes of project success, as in previous sections, i.e., Budget, Time, and Efficiency. This approach to separate different technologies allows research to isolate the impact of individual technologies rather than treating the Industry 4.0 concept as a homogeneous group. In the results, the significance was assessed to understand if the independent variable, in this case any separate technology, can predict the LSS project success from the perspective of the dependent variable, in this case Budget, Time, and Efficiency, to any degree. In reviewing the results, as in previous sections of the quantitative part of the research, the p-value serves as the primary metric. The significance level ($\alpha$) is set at 0.05 to determine if any specific technology has a statistically verified association with the project outcomes.

The results of Spearman's test for the association between Industry 4.0 technologies and LSS project success from a budget perspective can be seen in Table 11. Here, it can be seen that in general, the data shows a lack of association between the adoption of any specific Industry 4.0 technology and the LSS project's financial results. However, the review also shows a negative moderate level of significance in the association between LSS project success from a budget perspective and Robotics. The initial statistical test gave a p-value of 0.009, suggesting that LSS projects that involve Robotics tend to have a lower adherence to the initially planned budget. Practically, this might mean that the robotics initiatives often involve high integration costs due to complexity and hardware costs connected with automation. Despite this initial result, the validity of the result was further tested to control for chance findings across the tested technologies. Given that multiple simultaneous tests were conducted, a Bonferroni correction was applied to prevent the Type I errors, so-called false positive errors. The adjusted significance threshold was calculated as $\alpha_{adj} = 0.05/8 = 0.00625$. When compared against the stricter standard, the calculated p-value for Robotics is higher than the adjusted significance level, $0.009 > 0.00625$. Therefore, the association is statistically non-significant after correction.

In conclusion to this part, it should be noted that while the null hypothesis cannot be rejected, the near-miss result with robotics provides valuable insight. It suggests that while the majority of Industry 4.0 technologies have a neutral impact on budget, robotics implementation possesses a distinct financial risk profile that requires careful management of decisions connected with the LSS project where this technology is used.

Table 11. Correlation analysis of the LSS project success based on budget and Industry 4.0. Source: own research

| | | | **Variance in plan vs reality in budget** |
|---|---|---|---|
| Spearman's rho | Simulation | Correlation Coefficient | ,092 |
| | | Sig. (2-tailed) | ,479 |
| | | N | 62 |
| | Additive manufacturing | Correlation Coefficient | ,141 |
| | | Sig. (2-tailed) | ,273 |
| | | N | 62 |
| | Robotics | Correlation Coefficient | -,331** |
| | | Sig. (2-tailed) | ,009 |
| | | N | 62 |
| | Cloud computing | Correlation Coefficient | -,055 |
| | | Sig. (2-tailed) | ,669 |
| | | N | 62 |
| | Augmented reality | Correlation Coefficient | ,050 |
| | | Sig. (2-tailed) | ,697 |
| | | N | 62 |
| | Big Data | Correlation Coefficient | ,046 |
| | | Sig. (2-tailed) | ,725 |
| | | N | 62 |
| | Internet of Things | Correlation Coefficient | -,033 |
| | | Sig. (2-tailed) | ,801 |
| | | N | 62 |
| | Artificial Intelligence | Correlation Coefficient | ,041 |
| | | Sig. (2-tailed) | ,749 |
| | | N | 62 |

Following the estimation of the association between the usage of specific Industry 4.0 technologies and LSS project success from the budget perspective, the research proceeds with an attempt to perform the analysis of the association of the time dimension of LSS project success. This part investigates whether the adoption of specific digital technologies is associated with the ability of LSS projects to deliver better results from a schedule perspective. In this part, the study proceeds with the same methodology as in the previous, i.e., Spearman's Correlation test. The test was applied to assess the strength and direction of the relationship between separate Industry 4/0 technologies and the LSS project's success from a time perspective. The significance level remains the same at $\alpha = 0.05$, which is used to determine statistical validity before any necessary adjustments for multiple comparisons.

Table 12 summarizes Spearman's correlation results for Lean Six Sigma projects' success from a time perspective against specific Industry 4.0 technologies. A detailed examination of the p-values depicts a lack of association across the entire results set of Industry 4.0 technologies chosen for this study. From the statistical point of view, these coefficients indicate a negligible or very weak association, providing an idea that the variables are independent of one another for the given sample. It should be noted as well that the direction of the relationship fluctuates across the sample, as there are negative trends for the association between LSS project timeline and Simulation and IoT, as well as the positive trends for other technologies. However, these variations appear to be random rather than indicators of any pattern. Therefore, none of the correlations achieved the statistical significance level, as all calculated p-values are higher than the $\alpha = 0.05$.

To sum this part up, the analysis finds no empirical evidence within the given sample to support the idea that specific Industry 4.0 technologies influence Lean Six Sigma projects' success from the time point of view. Therefore, the null hypothesis cannot be rejected at this step of the analysis.

Table 12. Correlation analysis of the LSS project success based on time and Industry 4.0. Source: own research

| | | | Variance in plan vs reality on time |
|---|---|---|---|
| Spearman's rho | Simulation | Correlation Coefficient | -,101 |
| | | Sig. (2-tailed) | ,433 |
| | | N | 62 |
| | Additive manufacturing | Correlation Coefficient | ,098 |
| | | Sig. (2-tailed) | ,450 |
| | | N | 62 |
| | Robotics | Correlation Coefficient | -,079 |
| | | Sig. (2-tailed) | ,540 |
| | | N | 62 |
| | Cloud computing | Correlation Coefficient | ,068 |
| | | Sig. (2-tailed) | ,601 |
| | | N | 62 |
| | Augmented reality | Correlation Coefficient | ,168 |
| | | Sig. (2-tailed) | ,191 |
| | | N | 62 |
| | Big Data | Correlation Coefficient | ,133 |
| | | Sig. (2-tailed) | ,304 |
| | | N | 62 |
| | Internet of Things | Correlation Coefficient | -,049 |
| | | Sig. (2-tailed) | ,705 |
| | | N | 62 |
| | Artificial Intelligence | Correlation Coefficient | ,130 |
| | | Sig. (2-tailed) | ,314 |
| | | N | 62 |

The final phase of the influence of specific technologies of Industry 4.0 assessment is devoted to the analysis of the Lean Six Sigma project's success from an efficiency perspective. While budget and time measure constraints, efficiency often reflects the quality and the scope of the project's delivery. Thus, after the evaluation of budget and time, this part of the research deals with an empirical study by examining the association between specific Industry 4.0 technologies and the LSS project's success from an efficiency point of view. For the analysis, the same methodological framework was used as is used throughout this part of the research; that is, Spearman's correlation test was employed to assess the strength and direction of the association. The test correlates the usage of individual technologies against the dependent variable, that is, efficiency in this case, to determine if any specific digital technology contributes to a more efficient outcome. As with the previous part, the significance level is set at $\alpha = 0.05$ to validate any potential relationship.

The empirical results of the Spearman's correlation test for the LSS project's success from an efficiency point of view and individual I4.0 technologies are depicted in Table 13. As can be seen from the Table, statistical testing found no statistically significant association between the introduction of Industry 4.0 technologies and the efficiency of Lean Six Sigma projects. The results of this part are consistent with the findings for Budget and Time, as none of the examined independent variables, here as separate Industry 4.0 technologies, got a p-value below the required significance level of $\alpha = 0.05$, thus preventing the rejection of the null hypothesis. While Additive Manufacturing emerged as the variable with the most notable coefficient in this set, it also didn't meet the necessary criteria for statistical validation, as 0.098 is higher than 0.05.

These findings are along with the common conclusion of this section, thus making it stronger, that the mere presence of Industry 4.0 advanced digital technologies doesn't automatically change the LSS project into a successful project execution. Efficiency, as well as Budget and Time, seems to be driven also by factors other than individual digital technologies.

Table 13. Correlation analysis of the LSS project success based on efficiency and Industry 4.0. Source: own research

| | | | Variance in plan vs reality in efficiency |
|---|---|---|---|
| Spearman's rho | Simulation | Correlation Coefficient | -,110 |
| | | Sig. (2-tailed) | ,395 |
| | | N | 62 |
| | Additive manufacturing | Correlation Coefficient | -,212 |
| | | Sig. (2-tailed) | ,098 |
| | | N | 62 |
| | Robotics | Correlation Coefficient | ,172 |
| | | Sig. (2-tailed) | ,181 |
| | | N | 62 |
| | Cloud computing | Correlation Coefficient | ,077 |
| | | Sig. (2-tailed) | ,552 |
| | | N | 62 |
| | Augmented reality | Correlation Coefficient | ,014 |
| | | Sig. (2-tailed) | ,916 |
| | | N | 62 |
| | Big Data | Correlation Coefficient | ,174 |
| | | Sig. (2-tailed) | ,177 |
| | | N | 62 |
| | Internet of Things | Correlation Coefficient | ,076 |
| | | Sig. (2-tailed) | ,555 |
| | | N | 62 |
| | Artificial Intelligence | Correlation Coefficient | -,106 |
| | | Sig. (2-tailed) | ,413 |
| | | N | 62 |

To summarize the findings of the research regarding technological influence, a comprehensive statistical evaluation was performed to determine whether separate Industry 4.0 technologies could serve as a predictor for Lean Six Sigma projects' success. To analyze the combination, three critical success metrics typical for the project success determination were set as the Budget. Time and Efficiency. Spearman's Correlation test was applied to analyze the association between the mentioned success perspectives and eight distinct Industry 4.0 technologies, which are Simulation, Additive Manufacturing, Robotics, Cloud Computing, Augmented Reality, Big Data, IoT, and AI. The empirical results showed that there is a consistent pattern of independence between these dependent and independent variables. Across the majority of the test results' matrix, p-values were negligible and statistically nonsignificant. A single exception was observed between Robotics and Project's success from the Budget perspective, with $p=0.009$. However, to control the family-wise error rates, the Bonferroni correction was applied, and the p-value failed to meet the adjusted significance level of 0.006 and, thus, was stated to be rather a statistical artifact than a confirmed trend.

Based on the above-mentioned, it could be stated that no empirical evidence was found to support the claim that any specific Industry 4.0 technology is associated with improved or more successful LSS project results in the given sample. Therefore, the null hypothesis is retained, suggesting that any specific digital tool is not the primary determinant of the LSS project's success.

***Number of Industry 4.0 technologies and Lean Six Sigma projects success***

The second stage of this part of the research deals with the relationships between the total number of technologies introduced in the company and the LSS project's success. Specifically, the analysis attempts to investigate whether the higher number of Industry 4.0 technologies influences Lean Six Sigma projects' ability to be more successful from the point of view of Budget, Time, and Efficiency. To evaluate the potential association between variables, consistently with the previous parts, Spearman's correlation analysis was used. This method allows for the measurement of the strength and direction of the association between the number of Industry 4.0 technologies introduced in the company and the ranked project's success metrics implemented in the given research. The results of the analysis for all three dependent variables are depicted in Table 14.

As can be seen from the table, all coefficients are very close to zero, which suggests that there is no monotonic association between the number of Industry 4.0 technologies used and LSS project success. Moreover, all the p-values are higher than the required 0.05, which means that no significant influence between the two variables was found. Thus, the null hypothesis, stating that there is no correlation between the number of Industry 4.0 technologies and project success, cannot be rejected.

Table 14. Correlation analysis of the LSS project success and the number of technologies. Source: own research

| | | | **Variance in plan vs reality in efficiency** | **Variance in plan vs reality in budget** | **Variance in plan vs reality on time** |
|---|---|---|---|---|---|
| Spearman's rho | Number of technologies | Correlation Coefficient | ,031 | -,019 | ,111 |
| | | Sig. (2-tailed) | ,811 | ,882 | ,389 |
| | | N | 62 | 62 | 62 |

In summary, as can be seen from the above-mentioned, the assessment of Industry 4.0 technologies reveals a lack of association with the LSS project's success outcomes. The analysis demonstrates that neither the adoption of individual I4.0 technologies nor the total number of I4.0 technologies integrated into the company's activities serves as a predictor of the LSS project's success. Whether a LSS project uses a single technology associated with the Industry 4.0 environment or a set of digital solutions, the probability of meeting the project success goals from a budget, time, and efficiency perspective remained statistically unchanged. This unity across both parts of the research related to the technological environment leads to a robust conclusion that the Industry 4.0 technology alone is not a differentiator for LSS project performance in this sample. Therefore, the null hypothesis remains valid for both analytical parts, thus implying that the reasons for the successful project realization could be hidden in the methodology itself, leadership of team skills, rather than in an advanced technological environment.

## 4.5 Summary of findings

As the research employs a mixed-method design, composed of quantitative and qualitative parts (with the pilot research results also being considered), the summary of all findings is provided here to give an overview and integrate the results.

First, according to the Pilot study results, it is important to note that the combination of LSS and I4.0 is considered to be an effective combination that brings the benefits, especially from the process improvement and cost reduction points of view. A range of technologies, associated with I4.0 terminology, is used in companies for LSS projects, including IoT, Big Data, Robotics, Simulation, and Additive Manufacturing. Thus, the pilot study part of the research confirms that the applicability of modern technologies associated with Industry 4.0 possesses the potential to improve the LSS processes. This suggests a positive conjunction where LSS may also influence the smoothness of the introduction of these technologies.

Next, the qualitative part of the research suggests that the common understanding of Industry 4.0 is of the industrial environment, filled with a set of technologies where the processes are automated based on these technologies. The technologies that are associated with the term are Simulation, Big Data, Robotics, AI, and Cloud Computing. From the LSS point of view, the technologies that are currently used for the LSS projects include Cyber-physical Systems, Simulation, Sensors, Additive manufacturing, digital twin, and virtual reality. With the help of these technologies, the tasks of fast data processing, data analysis, and process optimization are the most important from the point of view of the I4.0 technologies usage. An important finding is connected with the barriers that can interfere with the successful and easy integration of the technologies in LSS projects, which are human factors (including reluctance and lack of knowledge), and investments that are normally associated with the introduction. As for the effectiveness and mutual benefit, the qualitative part clearly states that the influence of both I4.0 on LSS projects, as well as the structure of LSS and its influence on I4.0 technologies introduction, is beneficial for project improvement as well as cost reduction.

Finally, the quantitative part where the companies' characteristics, project characteristics, and Industry 4.0 technologies influence on the Lean Six Sigma project Budget, Time, and Efficiency was evaluated, clearly depicting the following:

1. No association was found between the company's characteristics considered in the research (namely, experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory) and LSS success from Budget, Time and efficiency perspective. Thus, we can conclude that the company's characteristics mentioned in the research are not the key to LSS project success.

2. No association was found between the project's characteristics, namely project budget, number of project participants, and LSS project success from the point of view of budget, time, and efficiency.

3. It was also evaluated that none of the technologies associated with Industry 4.0 (Big Data, AI, IoT, Cyber-Physical Systems, Robotics, Simulation, Additive manufacturing, Cloud Computing, Augmented reality) influence LSS project success from a budget, time, or efficiency perspective.

4. It was also found in the study that the number of Industry 4.0 technologies is not correlated with LSS project success from the budget, time, and efficiency point of view.

As it could be seen from the above mentioned, there was an interesting divergence found in case of the research, that is that the results of qualitative research where all the participants during the interview stated that there is a strong synergy between the Lean Six Sigma and Industry 4.0, the results of quantitative research are contradictory to that and shows that there is no direct association between I4.0 technologies and LSS Project success. This counterintuitive finding suggests that the mere presence of Industry 4.0 technologies introduced in the industrial company is necessary but not sufficient to predict LSS project success. This fact may point to the existence of a mediating latent variable that has not been evaluated in the given research, that is, "Human factor". Considering the fact that the human factor was mentioned several times and its importance was emphasized during the interview, this dependence seems quite probable; however, it was outside of the scope of the research given. This fact also aligns with the

Industry 5.0 concept, where it is considered that the presence of tools and technologies is ineffective as long as the human factor is ignored.

# 5. DISCUSSIONS

This chapter provides the summary and discussion, i.e., an interpretation of the study's results.

The purpose of this study was to gain an understanding of the role of Industry 4.0 technologies for Lean Six Sigma methodology and to understand the mutual influence of Lean Six Sigma methodology and Industry 4.0 technologies. In the scope of study, the summary of technologies used in Czech industrial companies both for LSS and in general was gathered, the barriers for the Industry 4.0 introduction were summarized, understanding of the beneficial conjunction of LSS and Industry 4.0 was assessed, and an estimation of how much LSS project success from budget, time and efficiency perspective is associated with company's characteristics, project characteristics and Industry 4.0 technologies (both, particular technologies and number of technologies).

The study consisted of quantitative and qualitative parts. For the qualitative part, 8 responses from the companies' representatives were gathered. Also, answers to open questions from the pilot study were considered in the qualitative part. For the quantitative research total of 62 responses were gathered from the companies, which were considered reasonable to be included in the research. For the quantitative part, the findings from the pilot study were included as a separate section of the research.

The findings of the research reveal that despite the fact that the statistical assessment of the influence of company's characteristics, project characteristic and Industry 4.0 technologies indicate that there is no significant impact of these on LSS project success, there are some general tendencies and common technologies that are already used in industrial companies (including LSS projects), and the qualitative part reveals the barriers that are connected with this integration and conjunction and confirms the mutually beneficial conjunction of LSS methodology and I4.0 technologies.

As it was stated above, a theoretical framework summarizing the literature review and data gathered is presented in the table developed for the given research. The framework is finalized in Table 15. The framework synthesizes the following: the type of technologies for the LSS process, the major aspects that the technologies are used for, technologies that influence project success, barriers to introduction, and the mutual influence of I4.0 and LSS. As the results from the theoretical study are depicted alongside the gathered results, the framework provides a structured comparison that connects theoretical and practical knowledge. This way of a framework summary allows the framework to be not only a theoretical summary but also a practical tool for guiding future applications of Industry 4.0 technologies and Lean Six Sigma methodology.

Table 15. The framework of the system of the conjunction of LSS and Industry 4.0. Source: own research

| **Literature review** | **Own research** |
|---|---|
| What Industry 4.0 technologies are used for LSS projects | |
| Big Data, Simulation, Cyber-Physical Systems, Robotics, Augmented Reality, Artificial Intelligence, Cloud computing, Internet of Things | Big Data, Simulation, Additive manufacturing, Robotics, AI, IoT, Sensors, Cyber-physical systems, digital twin, augmented reality |
| What are Industry 4.0 technologies used for | |
| Analysis of trends, root causes, and inefficiencies; Measurement of real-time data; Training; Monitoring and real-time control; Setup and maintenance; Mapping | Data collection, Data processing, Data reading, Problem finding, Problem solving, Process automation, Process optimization, Project creation, Solutions preparation, System self-correction |
| Barriers connected with Industry 4.0 introduction | |
| Lack of management commitment, investment/resources, technical factors, training, clear strategy and framework; skills (digital, analytical, learning); organizational culture and continuous improvement | Skills related, Human related, Investments related, data related |
| Industry 4.0 technologies that have the biggest influence on the LSS project success | |
| Big Data analytics; Simulation; CPS; robotics, AI, IoT | As for the price<br>Was not confirmed |
| | As for the duration<br>Was not confirmed |
| | As for the efficiency<br>Was not confirmed |
| Is LSS and Industry 4.0 is a beneficial conjunction | |
| Yes | It’s a positive conjunction that is not framed only by the technology’s introduction |

Following the framework mentioned above, it is important to note that the findings show that there are several Industry 4.0 technologies that are consistently integrated into LSS projects. These technologies are Big Data, simulation, and Cyber-physical systems, which are mentioned the most often. These technologies are primarily used for data-related tasks, which aligns with the previous findings where it is stated that new technologies could significantly improve the data analysis processes by being able to process large amounts of data in a short time, identify problems, and offer solutions (Sodhi, 2020), (Gupta, Modgil, & Gunasekaran, 2020).

The finding also suggests that LSS and Industry 4.0 can form a highly beneficial conjunction that will improve the setup of effective processes (from the qualitative part, however, the benefits, although being related to technologies, are not limited to them only). The idea that LSS should be a prerequisite for the introduction of Industry 4.0 is not novel and was already mentioned in previous studies (Arcidiacono & Pieroni, 2018), (Chiarini & Kumar, 2020), (Anvari, Edwards, & Yuniarto, 2020). It is connected with the fact that the improved process is easier to automate with new technologies than to invest in an unclear process with a lot of waste. Also, Industry 4.0 provides data access and data processing technologies that improve the DMAIC cycle and enhance the precision and speed up the process. At the same time, there are barriers that should be considered while introducing the new technologies, particularly the need for investment in training of the employees, which was confirmed in both the literature review and the gathered information. This aspect has also been discussed in previous works (Macias-Aguayo et al., 2022), (Rajak et al., 2024), (Antony, Vinodh, & Chakraborty, 2024), and others, however, in this research, an attempt was made to group the barriers, and 4 main groups were identified: human-related, skills-related, investment-related, and data-related.

While the results of the study didn't show correlation between LSS project's success form budget, time and efficiency aspect and company's characteristics such as company's size, company's industry, company's experience in LSS, certification in LSS, experience in Industry 4.0, active usage of Kaizen approach and Lean Six Sigma methodology, active trainings on LSS, active introduction of Industry 4.0 technologies and an attempt to create a Smart factory; project characteristics such as project duration, number of project participants and project budget; Industry 4.0, it could lead to the conclusion that project success is dependent on other mediating variables that have not been tested within the scopes of this research, thus, making the Industry 4.0 technologies although important part (that was proved in the qualitative part) not the sole influencing factor.

To sum everything up, it should be noted that based on the research results, it was proved that LSS methodology within the Industry 4.0 era has great potential to develop further by integrating the technologies to improve the data processing and possible solution offering. Although in the current time period and with the given sample, it was not confirmed that Industry 4.0 technologies have an impact on project success, both the pilot study and the qualitative study confirm the fact that the future perspective of the conjunction is positive, moreover, the combination of the necessity of the assessment of Industry 4.0 technologies with the human factor was mentioned in this research, thus, making this research close to the analysis of Lean Six Sigma methodology within Industry 5.0 environment.

# 6. CONCLUSIONS

This dissertation is set out to explore the integration of Lean Six Sigma methodology within Industry 4.0 framework with objectives to identify the influence of Industry 4.0 technologies on Lean Six Sigma projects and their contribution to projects’ success. It was determined to verify Industry 4.0 technologies that are used in LSS projects and reasons for their usage, to investigate the barriers that are connected with the introduction of the technologies, to asses the mutually beneficial conjunction of Lean Six Sigma and Industry 4.0 and to determine which factors influence LSS project success. The findings provide clear answers to all these research questions and contribute to both the theoretical and practical fields of process improvement.

First, the study establishes that there is a clear set of technologies, including Big Data, simulation, IoT, cyber-physical systems, robotics, AI, cloud computing, and augmented reality, that are increasingly being introduced to the LSS methodology. These technologies are used to improve multiple functions that are a part of LSS methodology ranging from data analysis, which is a core for the DMAIC methodology, via real-time data analytics, that using the sensors, cloud computing and IoT, can speed up the processes, to prepared solutions, where both the quick data access and AI provide a source to target the project more efficiently.

Second, the results summarize the barriers connected with the introduction of Industry 4.0 technologies. The most important barrier that was stated in the research is, the necessity of training and skilled employees, as, considering the complexity of the technological field, it is becoming inevitable in the contemporary world. Moreover, new technologies require considerable investments that could lead to the fact that some companies won’t be open to introducing the technologies to their practices in the nearest future. All the barriers are summarized into 4 main categories, that are people related (reluctance and fear of new), sills related (training, lack of qualification), investments related (high costs) and data related (data security and reliability).

Third, the results confirmed that the integration of LSS methodology within the Industry 4.0 framework is a mutually beneficial conjunction. The key aspect here is that Industry 4.0 provides enhanced data and analytical capabilities that enhance the efficiency and precision of LSS (especially from the DMAIC point of view), while LSS offers a structured methodological background to make the implementing the new digital tools smooth and optimized.

Fourth, the influence of such factors as the company's characteristics (experience with LSS, experience with Industry 4.0, LSS certificates, implemented Kaizen principles, active usage of LSS in the company, active training for LSS, attempt to introduce Industry 4.0 technologies, and attempt to create a Smart Factory), project characteristics (namely project budget, number of project participants and project budget), and applied Industry 4.0 technologies, together with the number of technologies applied, showed no evidence of being associated with LSS project success, which can be interpreted in such a way that these are although important but not only key parameters.

Following the previous two conclusions, the fifth point is important to be mentioned here, that is, the discrepancy between the qualitative results, which state that LSS methodology and Industry 4.0 mutually provide benefits, and the quantitative part results that failed to prove that these are merely technologies that are associated with the LSS project's success. This leads to the fact that there is a mediating latent variable that is out of the scope of this research and that might be related to the human factor. It could be the skills of those operating in a project and the knowledge and training of employees that contribute the most to the project's success, and that have already been mentioned as the barriers for the smooth introduction of Industry 4.0 technologies. However, these further factors have not been assessed in the scope of the given dissertation.

In conclusion, the research demonstrates that the Lean Six Sigma methodology has great potential within the Industry 4.0 era, as the possibilities that the introduction of new technologies can improve the methodology.

# 7. CONTRIBUTION

The intent of this study was to broaden the existing knowledge that can be further disseminated to LSS project managers.

From a theoretical point of view, this research will lead to an examination of the extent of the literature available on the investigation of the influence of Industry 4.0 on Lean Six Sigma methodology. As Industry 4.0 is a trend that gathers interest, this study will provide the necessary information and recommendations for further investigation. Moreover, the study will provide empirical evidence of the Influence of Industry 4.0 on Lean Six Sigma methodology. Also, the conceptualization of the integration of Lean Six Sigma in the scope of Industry 4.0 is manifested in the research.

The research provides the interpretation of the integration of Industry 4.0 technologies within a Lean Six Sigma framework, with the focus on how the technologies can improve the existing methodology and how to make the integration smooth. The ideas gathered in the research allow the researchers to have a deeper look at the integration of modern technologies into the industrial world and assess the benefits of this integration. Consequently, the research broadens the understanding of the current state of Lean Six Sigma methodology and provides a comprehensive analysis of the beneficial conjunction of Industry 4.0 and Lean Six Sigma. This could serve as a solid resource for future, more detailed studies with practical application of both separate technologies and the Industry 4.0 concept as a whole.

Furthermore, the research investigates what influences the LSS project's success from the point of view of budget, time, and scope, which could provide unique knowledge on the topic and could also improve further research that can be targeted at a more detailed assessment.

From a practical point of view, the results will provide practical information for practitioners of Lean Six Sigma and for companies willing to implement Industry 4.0 technologies. The findings will provide the information to overcome barriers connected with the introduction of Industry 4.0 or Lean Six Sigma. Moreover, a concept of linking Lean Six Sigma and Industry 4.0 technologies and the benefit of this merger for industries will be evaluated, which would provide companies with data for creating a framework for Industry 4.0 introduction.

As well as the mentioned above, the research will also help practitioners to set the priorities while integrating either Lean Six Sigma or Industry 4.0 into industrial life, or improving the existing processes.

As the idea that the Industry 4.0 technologies influence the speed, cost and effectiveness of LSS projects is proved in the research, this would mean that the costs for the company and for innovative processes are influenced, that would also mean that the companies position in the market competition will be greatly impacted by the contribution and implementation of the combination of Industry 4.0 technologies for LSS tools, LSS projects and LSS practices.

# 8. LIMITATIONS AND FURTHER RESEARCH DIRECTIONS

As with any research work, this work has its limitations that are summarized in this part, which, together with the divergence identified between the qualitative and quantitative, provide some future perspective directions for the scientific research, also mentioned in the given section.

The first limitation is the language barrier. As the research was done on a worldwide scale for a better understanding of the existing situation via the literature review, the language used for theoretical data gathering is English. However, as the research was performed in the Czech Republic, the research questionnaire for data gathering and communications with the specialists was performed in Czech. Summarizing this information, it should be, thus, noted that the research languages are limited to English and Czech. No other existing literature was considered in the research, nor were other communication languages considered for both qualitative and quantitative parts of the research.

The second limitation is the country. Although the country chosen for the research was analyzed from the point of view of providing the most reliable results, and the results can also be applied to other industrially developed countries in Europe, the results in other countries and cultures may vary from the results gathered in the given research.

The third limitation is the focus of the research on industrial companies. Considering the novelty of the topic, it was assumed that there were not many companies connected with services that could provide reliable data. However, the development of technologies is fast, and Lean Six Sigma has already been used in some other business sectors. That, while being a limitation for this research, could serve as a further research direction for future studies.

The last limitation, but not the least, is the period of the research. Considering the fact that Industry 4.0 is an emerging trend that is being actively developed, not all companies have sufficient experience with the technologies. As the implementation is fast, the results may change quickly. Thus, it may happen that with time, the results will be shifted, and future research may consider both the development over time. Furthermore, it should be stated that with the development and integration of the new technologies, it might possess a particular interest to validate the findings in several years and to consider further development of Lean Six Sigma methodology with the usage of Industry 4.0 technologies. Considering the findings of this research, which confirm that the conjunction is mutually beneficial, it might also be that the mutual influence will be considered.

Moreover, it could be seen that the topic is still in its infancy, with the rapid development of AI, the research focusing more on the AI influence on Lean Six Sigma projects possesses a particular interest. At the same time, it should be noted that apart from AI, other technologies that contribute a lot to the creation of the Industry 4.0 environment and their influence on the Lean Six Sigma project could also be evaluated independently, providing an important input to the theoretical and practical constituents of the topic.

Finally, as the discrepancy between the qualitative and quantitative data was found and was linked to a potential mediating latent variable of the human factor, the influence of the human factor should also be assessed in future research. Here, both the reluctance and fear of the staff, together with the skills of the workers, could be evaluated to identify their influence on LSS projects when combined with Industry 4.0 technologies. Or the Industry 5.0 synergy with Lean Six Sigma can be assessed from the point of identifying the key LSS projects' success factors from the constituents of Industry 5.0 terms.

To sum everything up, it should be stated that considering the complexity and rapid development of the topic, together with the fact that both new technologies and Lean Six Sigma are incorporated into the industrial companies as a part of environment and are interconnected and interrelated with other industrial processes, that makes it difficult to separate the influence of these notions from other industrial factors, it is important to note that the topic still has a lot of attention from both practical and theoretical perspective.

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# APPENDIX

A. Research questionnaire for qualitative study

**Výzkum je realizován v rámci doktorského studia, Integrace metodiky Lean Six Sigma v rámci Průmyslu 4.0.**

Anotace: Doktorský studium je realizován na Univerzitě Tomáše Bati ve Zlíně, na Fakultě managementu a ekonomiky. Disertační práce se zaměřuje na analýzu současného stavu Lean Six Sigma metodiky a integrace Průmyslu 4.0 ve firmách a jejích vliv na úspěšnost projektu.

1. Do jaké kategorie dle průměrného evidenčního počtu zaměstnanců zaměstnavatel patří?
   ☐ malá organizace (10–49 zaměstnanců)
   ☐ střední organizace (50–249 zaměstnanců)
   ☐ velká organizace (více než 249 zaměstnanců)
   ☐ nevím

   **Průmysl 4.0**
2. Jak rozumíte pojmu Průmysl 4.0?
3. Přijala vaše organizace nějaké technologie Průmyslu 4.0? Pokud ano, které a v jaké kapacitě?

| | ANO | NE | Komentář |
|---|---|---|---|
| Simulace | | | |
| Cloud | | | |

| | | | |
|---|---|---|---|
| Computing | | | |
| Additive manufacting | | | |
| Robotika | | | |
| Mobilní technologie | | | |
| Augmented reality | | | |
| Big Data | | | |
| Internet věci | | | |
| Cyber Fysické systémy | | | |

4. Jsou některé další technologie, které používáte a nejsou zde uvedeny?
5. K čemu tyto technologie využíváte a jaké další využití vidíte v těchto technologiích?
6. Jaké bariéry shledáváte při používání zmíněných technologií?
7. Jaké byly / jsou hlavní překážky pro implementaci technologií Průmyslu 4.0?

**Lean Six Sigma**

8. Používáte nastroje Lean Six Sigma ve vaší firmě?
9. Můžete stručně popsat svou roli a zkušenosti s implementací Lean Six Sigma (LSS) ve vaší organizaci?
10. Proč používáte/nepoužíváte ve svém podnikání nástroje Lean Six Sigma?

**Lean Six Sigma a Průmysl 4.0**

11. Integrovali jste nějaké technologie Průmyslu 4.0 do vašich projektů Lean Six Sigma?
12. Jaký vliv podle vás mají technologie Průmyslu 4.0 na efektivitu a úspěšnost projektů Lean Six Sigma?
13. Můžete uvést konkrétní příklady, kdy technologie Průmyslu 4.0 buď zlepšily, nebo zkomplikovaly úspěch projektů LSS?
14. Existují nějaké konkrétní technologie Průmyslu 4.0, které podle vás mají významný vliv na Lean Six Sigma? Proč
15. Jak efektivní je podle vás kombinace metodiky Lean Six Sigma a Průmyslu 4.0?
16. Mohl by Lean Six Sigma poskytnout pevný základ pro zavedení Průmyslu 4.0?
17. Jaké organizační výzvy jste zaznamenal(a) při integraci technologií Průmyslu 4.0 s Lean Six Sigma?
18. Jak vaše organizace podporuje přijetí technologií Průmyslu 4.0 v kontextu Lean Six Sigma
19. Jaké dovednosti nebo kompetence považujete za nezbytné pro úspěšnou integraci Průmyslu 4.0 s Lean Six Sigma?
20. Jak vidíte budoucnost Lean Six Sigma s rostoucí adopcí technologií Průmyslu 4.0?
21. Jak si myslíte, že se mohou organizace nejlépe připravit na budoucí integraci Lean Six Sigma s Průmyslem 4.0?

## B. Research questionnaire for quantitative study

### Vliv firemní kultury a Průmyslu 4.0 na Lean Six Sigma projekty

Vážený pane/Vážená paní,

jmenuji se Anastasia Efimova a v rámci doktorského studia, zaměřeného na zlepšování výrobních procesů, provádím dotazníkové šetření. Dovoluju si Vás požádat o vyplnění dotazníku a jeho zaslání do 30.04.2024. Výsledky jsou součástí mé disertační práce. Vyplnění by Vám nemělo zabrat déle než 15 min. Zaručuji Vám, že Vaše odpovědi jsou anonymní a že získané údaje budou sloužit výhradně pro výše uvedené účely. Případné nejasnosti, otázky či připomínky adresujte prosím mailem na **efimova@utb.cz**. Dotazníkové šetření je dobrovolné.

Předem Vám děkuji za podporu mého výzkumu. S pozdravem a přáním pěkného dne, Anastasia Efimova

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**Obecná informace**

Odpovězte prosím na následující otázky o vaší společnosti.

1. **Jaká je velikost vaší společnosti?**
   - o Velká (více než 250 lidí)
   - o Malá nebo střední (do 250 lidí)

2. **Na co se vaše společnost zaměřuje?**
   - o Automobilový průmysl
   - o Konstrukce
   - o Strojní zařízení
   - o Plastová výroba
   - o Potraviny a nápoje
   - o IT
   - o Zdravotní péče
   - o Jiné

3. **Uveďte prosím počet let zkušeností vaší společnosti s Lean Six Sigma**

   ______________________________________________________________________

__

4. **Uveďte prosím počet let zkušeností vaší společnosti s Průmyslem 4.0**

   ______________________________________________________________________

__

5. **Máte nějakou certifikaci Lean Six Sigma?**
   - o Ano
   - o Ne

6. **Uveďte prosím jaký certifikát**

   ______________________________________________________________________

__

7. **Jaké technologie Průmyslu 4.0 vaše společnost používá?**
   - Simulation
   - Cloud computing
   - Additive manufacturing

- Robotics
- Augmented reality
- Big Data
- Internet of Things
- Cyber Physical Systems
- Jiné

**8. Jaké technologie Průmyslu 4.0 používáte pro projekty Lean Six Sigma? K čemu je používáte? Jak je používáte?**

____________________________________________________________________________________

**Projekt Lean Six Sigma**

Vyberte jeden projekt DMAIC, který jste nedávno dokončili, a odpovězte na zbývající otázky

**9. Uveďte, jaké typy specialistů byly zapojeny do projektu, který jste vybrali?**

| | Ano |
|---|---|
| Yellow belt | |
| Green belt | |
| White belt | |
| Black belt | |
| Master black belt | |
| Lean specialista (bez certifikace) | |

**10. Jaká byla doba trvání projektu?**

- Do 1 měsíce
- Více než 1 měsíců, ale méně než 6 měsíců
- Od 6 měsíců do 1 roku
- Více než 1 rok

**11. Kolik lidí bylo zapojeno do projektu**

- Do 5 lidí
- 5 až 10 lidí
- 10 až 20 lidí
- Více než 20 lidí

**12. Jaké byly celkové náklady projektu v Kč?**

- Až 10000
- Více než 10000, ale méně než 50000
- Více než 50000, ale méně než 100000
- Více než 100000

**Úspěch projektu**

U stejného projektu, který jste vybrali, prosím odpovězte na následující informace o indikátorech úspěšnosti projektu

**13. Uveďte výslednou odchylku projektu**

| | Výsledek byl více jak 10% vyšší než plán | Výsledek byl 3% až 10% vyšší než plán | Žádná odchylka (+-2%) | Výsledek byl 3% až 10% nižší než plán | Výsledek byl více jak 10% nižší než plán |
|---|---|---|---|---|---|
| Rozdíl mezi plánovaným a skutečným rozpočtem | | | | | |
| Rozdíl mezi plánovaným a skutečným trváním | | | | | |
| Rozdíl mezi plánovaným a skutečným výsledkem (efektivita projektu) | | | | | |

**14. Popište dopad odchylky (předchozí otázka) na project**

| | Bez dopadu | Nízký dopad | Průměrný dopad | Velký dopad |
|---|---|---|---|---|
| Rozdíl mezi plánovaným a skutečným rozpočtem | | | | |
| Rozdíl mezi plánovaným a skutečným trváním | | | | |
| Rozdíl mezi plánovaným a skutečným výsledkem (efektivita projektu) | | | | |

**Průmysl 4.0**

U projektu, který jste vybrali, prosím uveďte technologie, které byly použité.

**15. Uveďte, zda pro svůj projekt používáte jednu nebo více z následujících technologií (v jakékoli fázi projektu)**

| | Ano |
|---|---|
| Simulation | |

| | |
|---|---|
| Additive manufacturing | |
| Robotics | |
| Cloud computing | |
| Mobile technologies | |
| Augmented reality | |
| Big Data | |
| Internet of Things | |
| Cyber Physical Systems | |

**16. Považujete spojení Průmyslu 4.0 a metodiky Lean Six Sigma za vzájemně výhodné?**

- Vůbec ne
- Jen v několika bodech
- Možná v některých situacích
- Více ano než ne
- Určitě ano

**17. Jaké výhody a bariéry má kombinace Lean Six Sigma a Průmysl 4.0**

______________________________________________________________________________

**Lean Six Sigma a Průmysl 4.0 v naší společnosti**

Odpovězte prosím na následující tvrzení podle následujícího:
1 - naprosto souhlasím, 2 - částečně souhlasím, 3 - neutrální postoj, 4 - spíše nesouhlasím 5 - absolutně nesouhlasím

**18. Lean Six Sigma v organizace**

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Máme zavedenou politiku neustálého zlepšování | | | | | |
| Naše organizace poskytuje programy a workshopy, které se zaměřují na neustálé zlepšování | | | | | |
| Aktivně používáme principy štíhlé výroby a Six Sigma | | | | | |

**19. Průmysl 4.0**

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| V naší organizaci snažíme se zavést nové technologie | | | | | |
| V naší organizaci snažíme se vytvořit podnik průmyslu 4.0 (propojujeme činnosti pomocí digitálních prostředků) | | | | | |

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IGA/FaME/2021/002 Performance analysis of container yard for the dwell time and reshuffle: A smart port 4.0 perspective to monitor the hazards of logistics processes

IGA/FaME/2022/005 Industry 4.0 and Circular Economy Adoption for Manufacturing and Logistics Processes.

IGA-K 2022 Smart přístup ve vzdělávání studentů FAME.

RVO 2023 Vybrané aspekty řízení lidských zdrojů podporující inovativnost jako klíčový faktor výkonnosti organizací

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# Integration of the Lean Six Sigma methodology within the Industry 4.0 framework

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