Enhancing Lean Manufacturing Utilizing Industry 4.0 Technologies

A Focus on Cyber-Physical Systems

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The industry is a significant part of our economy, providing our material goods in a highly mechanized and automatized way. The industry has gone through three acknowledged revolutions, and now the industry is on the verge of the fourth industrial revolution as known as Industry 4.0. Industry 4.0 surfaced in the 21st century and has gained interest exponentially after 2016. However, the research on this topic is still in its early stages. Thus, this has been taken into account as the research is conducted on a more specific topic.

Industry 4.0 composes of many different technologies, from which the main focus of this thesis' is on Cyber-Physical Systems and what they might offer to Lean Manufacturing. The aim of this thesis is also to provide basic knowledge of lean and Industry 4.0 in general so that it allows more profound exploring of Cyber-Physical Systems and helps to perceive the possibilities more extensively. This thesis also presents significant concerns regarding the use of Cyber-Physical Systems. Based on these topics, the conclusion can be formed to answer what possibilities Industry 4.0 offers.

The main findings from this literature review prove that Industry 4.0 and Cyber-Physical Systems can offer a great variety of possibilities to Lean Manufacturing. As it is debated that Lean Manufacturing, as is, is reaching its limits, implementing Industry 4.0 technologies is becoming crucial to maintain competitive capability. Cyber-Physical Systems could offer enhancement through streamlining the manufacturing process, reducing waste and workload, and better deficit and abnormality detection, for example. As a contribution, this thesis provides information in a chronological order to provide extensive enough understanding and an answer to the research question.

Keywords Lean Manufacturing, Industry 4.0, Cyber-Physical Systems, Efficiency, Industry

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Abbreviations

IoT = Internet of Things

AI = artificial intelligence

CPS = Cyber-physical systems

CPPS = Cyber-physical production system

JIT = Just-in-time

Industry 4.0 = Fourth industrial revolution

SCM = Supply Chain Management

ERP = Enterprise Resource Planning

RCS = Resilience control system

TPS = Toyota production system.

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1 Introduction

The principles of Lean Manufacturing originate from the Japanese manufacturing industry, founded by T. Ohno at the company called Toyota-GM. "Its simplicity and high effectiveness had been the reason why Lean Production became famous in the 1990s" (Kolberg and Zühlke, 2015; Mrugalska and Wyrwicka, 2017). The increasing need to be able to answer customer needs as agile as possible, and pressure from global competitors made many manufacturing companies adapt to competition and adopt the practice of Lean Manufacturing and principles.

The main principle of Lean is to create efficiency, streamline production while minimizing waste with the synergy of using the Lean practices together. Applying Lean practices and adapting to Lean methodology usually results in decreased lead times, better inventorying, improved resource management, and better and more robust processes. The philosophy of Lean thrives for continuous improvement and improving productivity with fewer costs through the supply chain.

The idea of automating Lean has been around for over two decades, and now through the arrival of Industry 4.0, the fourth industrial revolution, technologies are becoming more recognized, and the possibilities of the Lean automation are becoming realistic. Industry 4.0 is a driver for Lean principles, making Lean automation finally possible when executed right. How can we utilize these to make Lean practices even more streamlined, generate less waste, and create more efficiency? Now that the integration of powerful, flexible, and finally, more affordable cyber-physical systems, Internet of Things, Artificial Intelligence, and smart systems are possible, the idea of Lean Automation is becoming possible (Kolberg and Zühlke, 2015).

1.1 Motivation and research question

The motivation for conducting a literature review of this topic is quite essential, as Lean Manufacturing was the divisive factor more than two decades ago, making the companies that utilized Lean way more efficient and competitively relative. The future of the companies utilizing Lean methodologies depends heavily on how well they can adapt and utilize the technologies. The success of industry 4.0 technology usage can widen the gap between other companies in the same field of business drastically. So, the usage of industry 4.0 technologies can be perceived as a strategy to gain a competitive edge towards competitors. It has been showcased that the integration of Industry 4.0 and innovative automation technology has great potential, but the lack of comprehensive frameworks, which combines Lean and Industry 4.0, slows down the process initialization of potential. It is recognized that Lean Manufacturing and Industry 4.0 synergized can bring value to users (Kolberg and Zühlke, 2015). This literature review seeks to answer the following question:

1. How can we enhance Lean principles by utilizing the potential technologies that Industry 4.0 offers?

2. How can Industry 4.0, particularly Cyber-Physical Systems, be utilized in different areas of Lean Manufacturing?

How can the basic two principles of Lean, creating value, and generating less waste, be carried out even more efficiently? The objective of this thesis will be to find various potential approaches to utilize Industry 4.0 technologies to create value throughout the manufacturing process. The analysis of possibilities will be divided into three categories that resemble the pillars of Toyota Production Systems, A famous Lean manufacturing model, and its base layer. This research will revolve around already recognized technologies, primarily the Cyber-physical systems, which could provide value and enhancement to Lean Manufacturing in various ways. Cyber-Physical Systems are a combination of technologies that Industry 4.0 offers; for example, a CPS can utilize sensors, IoT, and AI. To reach the fulfillment of the research question, it will require a comprehensive understanding of the concepts of Lean principles, what is the reason behind the need for enhancement and Industry 4.0. Understanding the background of the mentioned concepts will help in understanding the possibilities of making Lean Manufacturing more efficient. This research will highlight the possibilities that the usage of Industry 4.0 technology brings in exchange with possible risks, failures, and challenges in implementation. The development of companies using Industry 4.0 technologies could have a massive impact on the market dynamics across industries.

1.2 Scope of research

The objective of this thesis is to provide a preliminary analysis of how Industry 4.0 technologies can, especially Cyber-Physical Systems, be used to enhance Lean Manufacturing and review the possibilities, risks, and challenges they bring. Providing an extensive understanding of all of Industry 4.0 technologies and explaining all of the possibilities comprehensively how to create value by utilizing them is out of the scope of this thesis. Going over Lean Manufacturing extensively will not be included except the basics of Lean principles and a summary of Lean's theoretical background. This research will be done in the form of a literature review to address the research questions. This thesis will be focusing on the technical and economic relation in Industry 4.0.

1.3 Structure of the research

The thesis will follow the structure of a predetermined coherent structure; beginning includes an abstract, a table of contents, information about abbreviations, a list of tables and figures. The first chapter is an introduction, which contains motivation and research questions, scope, and the presentation of the thesis structure. Chapter 2 goes over the conceptual background and conceptual framework. Chapter 3 presents the used methodological approach for this thesis. Chapter 4 introduces findings in the literature about Industry 4.0 technologies, and this chapter will firstly cover the fundamentals of Industry 4.0 and Cyber-Physical Systems. The second part of the chapter introduces why Industry 4.0 is starting to be relevant and how could the implementation of CPS's effect Lean Manufacturing's different areas. After the brief introduction of this part, analysis of the uses and possibilities Cyber-Physical Systems offer, are presented and how can they enhance different Lean methodologies. Chapter 5 will go over the challenges and risks affiliated with the possible implementation of the Industry 4.0 technologies and Cyber-Physical Systems. Chapter 6 presents the reader with a discussion about the subject as well as concluding the thesis', and finally going over some limitations relating the thesis' and how could the research about the topic and research about Industry 4.0 be continued.

2 Conceptual Background

The objective of this chapter is to prepare the reader with some conceptual background of Lean Manufacturing and Industry 4.0 separately and then presents the conceptual connection. This chapter helps to identify the connection between these two concepts and make it clear how Industry 4.0 might be the natural extension or continuum of Lean Manufacturing.

2.1 Lean Manufacturing

After K. Toyoda and T. Ohno observed Ford factories after world war II, they saw potential in the methodologies that Ford used. After seeing Ford's systems using machine and workstation optimization, Toyota realized and saw more potential in optimizing overall product flow throughout the whole process because the Ford system was not flexible enough. Throughout the years, Toyota made small innovations in the areas of quality control, designing better process layouts, improving layouts to enable JIT with the support of Kanbases and production pull, and creating an efficient management system to support these principles. The innovations are synergizing with each other accumulated into shorter lead times, diminishing the warehousing needs and ability to react to the market's needs. Toyota had created a baseline for Lean principles, which has been simplified into two basic concepts, eliminating waste and creating additional value (Čiarnienė and Vienažindienė, 2012). According to Womack and Jones (1997), Lean Manufacturing is composed of five principles:

1. Identifying customer needs,
2. Identify and map the value stream,
3. Create flow by eliminating waste,
4. Response to customer pull
5. Pursue perfection

2.2 Industry 4.0

As a field of study, industry 4.0 is a very recent topic; it has gained attention increasingly during the 21st century, mostly after 2016. Industry 4.0 was very long undefined what it consists of, and it still maintains a broad spectrum of different ways how to define it. In theory, Industry 4.0 tries to respond to the question: How companies can answer to increasingly quickly changing consumer demands and shorter product lifecycles? Term industry 4.0 is understood as the fourth industrial revolution, which stands for the digitalization of the industry, digitalizing vertical and horizontal processes through the value chain, combining information and communication technology with manufacturing. Industry 4.0 has become more relevant due to many signs that the current practices of resource usage are not sustainable, which will, in the long run, limit the production levels (Gubán and Kovács, 2017; Lele, 2019). Industry 4.0 defines three main topics, according to Zezulka *et al.* (2016) and Reinhard, Jesper and Stefan (2016), which will affect the corporate world, which is:

1. The digitalization of industrial and economic relations
2. The digitalization of products and services,
3. New market-related models

Federation of German Industries (BDI) states: "Industry 4.0 paves the way for personalized products, efficient resource logistics, new services, and a more flexible working environment." (Klein, 2019). The purpose of these is to state that the concept of Industry 4.0 is still quite vast, and the main focus of this thesis will be on the digitalization of industrial and economic relations with a focus on value creation, especially in the Lean Manufacturing field.

Now that the concept of Industry 4.0 has gained more attention and people have understood that it might be the solution for the future of manufacturing, companies have started slowly to invest in and adopt technologies of Industry 4.0. However, still, the uncertainty and unfamiliarity of the topic are slowing down the implementation on a larger scale. The development of Industry 4.0 needs a very innovative environment to reach its full potential.

It is fascinating to note that most significant researchers on the Industry 4.0 topic are Germany, the United States, and China, with Germany having the most substantial input on the research. The facts mentioned above indicates a high interest in the topic by the countries which have a lot of highly developed industry and the interest to create more value with sustainable methods. Germany is evolving to be the frontrunner in the Industry 4.0 market and to be a supplier for Industry 4.0 solutions due to its high impact on worldwide research. Albeit this thesis will not follow any predefined framework due to the unique nature of this research paper.

In the future, when the technologies provided by the concept are more widely tested and understood, it will be the most effective and value-creating one's merge to the companies that can benefit from them.

2.3 The Conceptual Shared Purposes

Lean manufacturing has been arguably the most notable manufacturing paradigm of recent times, according to Womack, Jones and Roos (1992), it has been debated that Industry 4.0 technologies are the continuum of Lean Manufacturing. Although there have been numerous recent studies about Lean manufacturing and Industry 4.0 solely, there are few that address the possibilities these two would have when synergized. Lean originating from the Toyota Production Systems was initially completely independent of any information communication technologies. However, the emergence of efficient ICT solutions is useful in creating efficiency in the area of Lean Manufacturing (Kolberg and Zühlke, 2015; Buer, Strandhagen and Chan, 2018).

Roy, Mittag and Baumeister (2015) argue that Industry 4.0 and Lean manufacturing are not concepts that eliminate each other but rather synergize well and help to mature the Lean methodologies used in the companies. It is predicted that the integration of Industry 4.0 technologies into Lean Manufacturing will be done gradually, increasing the flexibility, productivity, reducing costs, and improving quality (Buer, Strandhagen and Chan, 2018). Khanchanapong *et al*. (2014) found that the two combining the concepts has a great synergistic performance impact versus utilizing either alone.

According to Jackson *et al.* (2011), the Lean automation-concept surfaced in 1990. The concept concerns the development of automation solutions with a low level of complexity that fits in to lean production environments. Now, that Industry 4.0 is surfacing and the similarities are recognized, have this reignited the need for research regarding the possibilities that Lean automation could bring, now alongside with Industry 4.0 (Kolberg and Zühlke, 2015).

3 Methodology

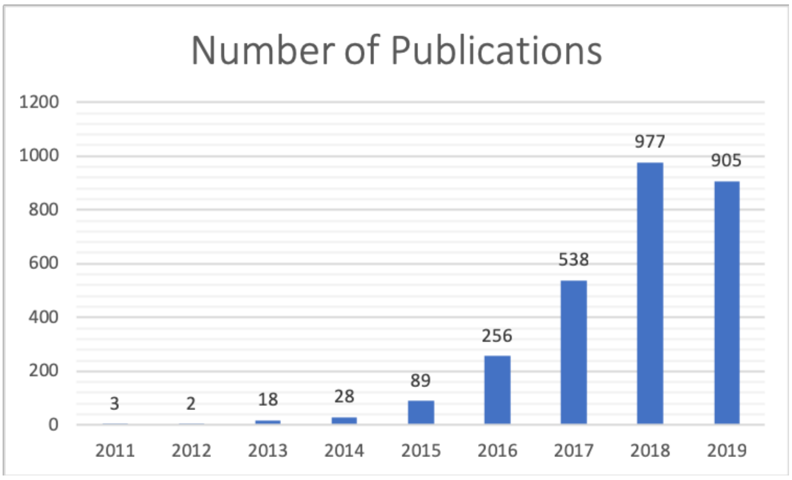
The focus of this review is to find qualitative information from different scientific databases to create a foundation for this thesis and to be able to answer theoretical questions about the possibilities Industry 4.0 offers for manufacturing. This thesis will be structured on current knowledge available about the subject, selecting the sources with a focus on most recent and thorough ones. Furthermore, executing this research as a theoretical, qualitative literature review is the most suitable approach for the subject due to very little concrete and numerical evidence and the theoretical nature of Industry 4.0 to manufacturing in general. Understanding the theoretical side of Industry 4.0 helps in understanding how the technology and manufacturing concepts offered by Industry 4.0 will possibly be implemented. Taking the novel nature of the subject of this thesis into account, the thesis is structured to support understanding the concepts with as little initial information as possible.

3.1 Finding the Right Data

Using Scopus[1], a peer-reviewed literature database, to find articles addressing the Industry 4.0 manufacturing-topic, resulted in 2,905 (01.01.2011-14.11.2019) documents. Scopus and another scientific search engine called Google Scholar[2] was primarily used to create the foundation for this thesis. Searching articles and scientific papers using the keyword "Industry 4.0 manufacturing" generally results in articles that address a particular area or application of Industry 4.0 manufacturing and not the Industry 4.0 manufacturing in a comprehensive manner. Coupling specific keywords to Industry 4.0, such as *Cyber-Physical Systems, fundamentals, challenges and risks, IoT, Value creation*, provided more convenient papers towards different subjects reviewed throughout the thesis. The data utilized is mostly post 2016 due to the significant growth in research, evidence, and interest regarding Industry 4.0 manufacturing in 2016 and after. The following figure (Figure 1) presents the growth of interest regarding the topic. It presents the different numbers of publications for every year from the start of 2011 until 14.11.2019:

[1] www.scopus.com
[2] https://scholar.google.com

Figure 1. Number of Publications per Year



Source of the numbers: Scopus 2019

The aim was to find papers and articles that cover different topics regarding Industry 4.0 Manufacturing. Firstly, the focus was on finding research papers that can be referenced to and use for covering and explaining the basic features of Lean and Industry 4.0 manufacturing. After laying out the foundation, the next articles and whitepapers that were utilized go over the possible applications of Industry 4.0 in the future, tried to use as recent research as possible to find the most relevant information. Why the main focus is research on the connection between Industry 4.0 manufacturing and Lean principles are because a large proportion of the research papers about Industry 4.0 focuses on some field of manufacturing-related technology. When selecting papers and whitepapers to refer to throughout the process of researching, the focus was on the ones which are the most relevant, based on citations and significance towards the field of research. Furthermore, the foundation and the basics have written using sources that are remarkable, but also recent. The literature about the applications and possibilities provided by Industry 4.0 manufacturing technologies is more novel and experimental. The whitepapers chosen used more theoretical and remarkable sources as the foundation.

3.2 Sources Throughout the Thesis

The findings of this literature review are split into two sections. The first section focuses on the descriptive analysis of the technologies and possibilities Industry 4.0 offers regarding this thesis's subjects. The purpose of the first section is not to explain and cover all of the technological possibilities Industry 4.0 brings to manufacturing, but the ones important regarding the thesis's scope and to be able to understand the basis of the technologies addressed in the second section. The second section is based on the theoretical foundation established in the first section and presents different ways how could Cyber-Physical Systems be applied to Lean Manufacturing and Create Value. The selection of these two sections and their sub-sections is meant to help build coherence and present findings in a chronological order to ease understanding the concepts. Furthermore, following this structure helped to gather data from different sources with different approaches and gather the most relevant data regarding the sections. There was no available already created framework, that could have been utilized to conduct this particular research efficiently.

Although the sections mentioned above use variable articles depending on the focus, the introductory part, which lays the foundation of this literature review, uses mostly the articles and research provided by Womack and Jones (1997) and Kolberg and Zühlke (2015). Womack and Jones's (1997) article ‘Lean thinking−banish waste and create wealth in your corporation’ lays out the foundation of Lean principles and presents the idea of Lean automation, which Kolberg and Zühlke (2015) utilizes in reviewing the possibilities how Industry 4.0 could enable Lean automation in their article ‘Lean Automation enabled by Industry 4.0 Technologies’.

The latter parts utilize a great variety of sources, due to the restricted scope of the most articles used. However, The Fundamentals of Cyber-Physical Systems is heavily based on Lee, Bagheri, and Kao's (2015) model of the 5C architecture. In their whitepaper ‘A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems’, a model for Cyber-Physical Systems is presented in a very clarifying form, that eases the understanding of the possible structure Cyber-Physical Systems could acquire. This very vital when trying to understand the possibilities they bring to Lean Manufacturing, presented in the latter parts of the thesis.

4 Creating Value in Lean Manufacturing Utilizing Industry 4.0 Technologies.

This chapter will present the findings about Industry 4.0 and Cyber-Physical Systems fundamentals. After the fundamentals have been laid out, the possible applications of Cyber-Physical Systems to Lean Manufacturing are presented split into three parts.

4.1 Findings in Literature Review of Industry 4.0 Technologies

The relatively low number of scientific articles and detailed research about the topic is a consequence of the Industry 4.0 manufacturing – concept's novel nature, as the topic has been around only less than a decade. The literature review about the topic splits up to 4 subsections, first part going over the state of fundamentals and framework of Industry 4.0 and the speculative future. The second part explains the possible future of production and manufacturing with the usage of Industry 4.0. The third part explains the possible implementations of Industry 4.0 technology (CPS, IoT, Smart factories), Also going over horizontal –/ vertical integration and end-to-end integration. The fourth part reviews possible challenges in implementation, for example, different systems in production and manufacturing. These four applications of Industry 4.0 are a suggested baseline for further understanding of the topic and the impact Industry 4.0 might have in the future. Also, given all the concepts and research so far, opinions among researchers and practitioners differ about the future and how will Industry 4.0 impact in practice.

The following table (Table 1) summarizes the critical sources used in the following literature review chapters and how they connect to the phenomena and topic. The table also showcases how the articles are connected to Lean Manufacturing and Industry 4.0 and what areas the articles address.

Table 1. Summary of literature

Source	Statement	Lean as base for Industry 4.0	Industry 4.0 completes Lean	Industry 4.0 could increase Lean efficiency
Rüßmann *et al.* (2015)	Industry 4.0 presents tremendous opportunities for innovative producers			X
Tjahjono *et al.* (2017)	Industry 4.0 implementation presents clear benefits which are flexibilty, quality standards, efficiency and productivity			X
Mrugalska and Wyrmicka (2017)	Different ares of Industry 4.0 references to Lean Principles heavily	X	X	X
Bagheri *et al.* (2015)	Utilizing advanced analytics of Cyber-Physical Systems provides network of machines with ability to perform more efficiently, collaboratively and resiliently		X	X
Ahmadi *et al.* (2018)	Cyber-Physical Systems is one of the most promising Industry 4.0 techonology regarding manufacturing			X
Monostori (2014)	CPPS and CPS can be considered as an important step in the development of manufacturing systems			X
Prinz, Kreggenfeld and Kuhlenkötter (2018)	Organizations have to be optimized to Lean aspects to be able to implement digitization succesfully	X	X	X
Wagner, Herrmann and Thiede (2017)	Industry 4.0 applications can stabilize and support Lean principles	X	X	X
Romer *et al*. (2019)	Minimizing digital waste in the digitalization process leads to improved digital Lean value.		X	X
Ansari *et al.* (2018)	Autonomation, with human-machine interaction can develop Lean practices (Jidoka)	X	X	X
Ustundag and Cevikcan (2018)	Lean Manufacturing and Industry 4.0 can be seamlessly integrated with each other for successful production management	X	X	X
Kolberg and Zühlke (2015)	Cyber-Physical Systems accelerates the Lean philosiphies.		X	X

4.1.1 Fundamentals of Industry 4.0

In short, Industry 4.0 is a German initiative that thrives on finding a solution as to how the increasing requirements of cost efficiency, flexibility, adaptability, stability, and sustainability can be answered through the digitalization of manufacturing. Industry 4.0 will play a crucial part in a global transformation of the manufacturing industry in the areas designing better manufacturing processes, services, and operations through digitizing, technology offered by Industry 4.0 will shift the nature of work in manufacturing.

Industry 4.0's foundation is based on the use of big data, IoT and Artificial Intelligence, Simulation, autonomous robots, Augmented Reality, The Cloud, Additive manufacturing, cybersecurity, and horizontal- and vertical integration. At the moment, companies have adopted some of these technologies but use them separately and in isolated cells. Industry 4.0 aims at combining these all together in a synergized, fully integrated system, which includes all the aspects to gain synergy advantages. The efficient use of these drivers synergized will be making Industry 4.0 technologies and, for example, Cyber-Physical Systems efficient and to be able to communicate as a whole. Using these concepts, as mentioned earlier, synergized at large allows the smart machines/factories to learn and analyze the processes and understand and pinpoint the production issues and bottlenecks. With adequate usage, the technologies can help out minimize waste in areas of labor and materials, leading to growth inefficiency (Rüßmann *et al.*, 2015; Tjahjono *et al.*, 2017).

In order for the industry 4.0 technologies to be applicable for companies, a certain level of prerequisite technology is required, meaning the companies will have to reach a certain level of technological maturity to be able to utilize Industry 4.0 solutions. An example of the maturity model and an index number, a World Economic Forum's Global Information Technology report in 2016, stated the countries that are most ready for the industrial revolution and will be benefitting from the investments made towards infrastructure in communications technologies (ICT). The index number was based on the state of the countries regulatory and business environment, countries' state of ICT, the level of engagement of stakeholders, and the impact of the use of technologies. With these metrics, Singapore and Finland are at the moment the most prepared countries to implement Industry 4.0 technologies (Mehta *et al*., 2019).

Table 2. Network Readiness Index

Rank	Country	Network Readiness Index
1	Singapore	6,0
2	Finland	6,0
3	Sweden	5,8
4	Norway	5,8
5	United States	5,8
6	Netherlands	5,8
7	Switzerland	5,8
8	United Kingdom	5,7
9	Luxemburg	5,7
10	Japan	5,7

Source of the figure: Mehta et al. (2019)

4.1.2 Fundamentals of Cyber-Physical Systems

Cyber-Physical Systems are defined as transformative technologies, which manage interconnected systems between computational capability and physical resources. CPS is considered to consist of two main components. Firstly, the components that allow connectivity and advanced real-time data transferring between the system, real-world/humans, and cyberspace. The second component is data management, analytics, and computational capability, which constructs the cyberspace. With the recent development in the field of sensors, data mining and data acquirement systems lead to them being more affordable and applicable. Coupling the progress as mentioned above with the competitional force that Industry 4.0 brings, have companies started to try to find ways of implementing Cyber-Physical Systems (Lee, Bagheri and Kao, 2015).

Table 3. Comparison of Industry 4.0 Factories and Present Factories

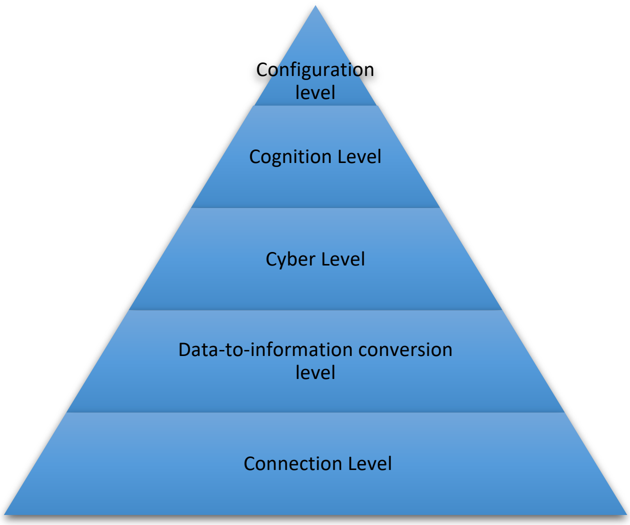
	Present factories		Industry 4.0 Factories	
	Attributes	Technologies	Attributes	Technologies
Components using sensors	Precision	Smart sensors and fault detection	Self-awarness and -predictability	Degradation monitoring and life prediction
Machines and controllers	Productibility and performance	Monitoring and diagnostics	Self-awarness, -predictability, -comparement	Better control of uptime and predictive health monitoring
Production systems, with networked connection	Productivity and overall resource effectiveness	Lean operations: waste and work reduction	Self-configuration, -maintaining, -organizing	Nearly automatic production

Source of table: Bagheri et al. (2015)

Table 3. showcases how modern factories differ from an Industry 4.0 factory with CPS being implemented. Cyber-Physical Systems will automate a considerable proportion of a factory's workload, being able to track and manage production/uptime, being able to track components, machines, and different unit degradation levels and health. The usage of sensors can be extended from only detecting faults to predicting faults and being aware of the manufacturing process. Machines' and controller's producibility and performance will be enhanced with proper implementation of Cyber-Physical Systems to being able to control the uptime of production and monitor the health of the machinery with self-awareness and being able to predict the usage. Upgrading the production systems with a connected network will enhance the Lean principle: waste and work reduction, with the process becoming almost automatic, the efficiency will grow. All of these enhancements will require the proper implementation of a CPS, forming a unified structure that supports data transferring throughout the process. A Cyber-Physical System will help to enhance resource efficiency, reliability, and overall quality of the process and the product.

To create a unified structure for the CPS which covers the whole process, a theoretical 5C architecture model (Figure 2) has been developed by Lee, Bagheri and Kao (2015) for a guideline to building an efficient CPS, which uses Industry 4.0 base technologies (represented in chapter 4.1.1) in a synergized way.

Figure 2. 5C Architecture for CPS



Source of the figure: Bagheri et al. (2015)

The first level of the model represents the interconnection of the machines and their components and data-acquirement. With the correct usage of devices, for example, different kinds of sensors altered to fit the situation, data can be acquired and collected throughout the process. With the proper use of sensor networks, controllers, and enterprise manufacturing systems such as SCM or ERP can the primary factors of this level be accomplished, allowing a seamless, tether-free, and accurate data acquirement process and data transferring to the central servers. The proper implementation enables condition monitoring for the systems. IoT technology will be used to realize the data into relevant information and linking the systems (Bagheri *et al.*, 2015; Ahmadi *et al.*, 2018).

The second level represents the conversion of the data. This part covers separating the meaningful and useful data from the acquired data masses and turning it into relevant information. With the application of IoT or through other analytical tools, the information can be analyzed and used for prognostics and analyzing health values. This level enables self-awareness for the machines, and for example, remaining useful life can be tracked (Bagheri *et al.*, 2015; Ahmadi *et al.*, 2018).

The third level of the model, the Cyber level, is arguably the most important one. The cyber level is the central point of information, connecting the systems and machines in the CPS network while gathering information from the whole system. With specific analytical tools, tools, the massive amount of gathered information can be used to harvest specific and useful information, which provides information about the machinery in the system? Through these analytics, the machines' performance can be compared to other machines, enabling the self-comparison ability for the machines in the CPS. The historical data and the data about similarities between machines can be used to predict the future behavior of the machines (Bagheri *et al.*, 2015; Ahmadi *et al.*, 2018).

The implementation of the fourth level, the Cognition level, requires extensive knowledge of the system and well-functioning previous levels. If the CPS has been implemented correctly up to this level, the system generates thorough information. The Cognition level requires this comprehensive and detailed information to present to the experts to support their decision making. Since the quality and quantity of available information varies greatly, proper infographics are necessary to support the experts' ability to prioritize insights in decision making. This level allows the collaborative decision making, mutual learning, and diagnostics between the CPS and the experts (Bagheri *et al.*, 2015; Ahmadi *et al.*, 2018).

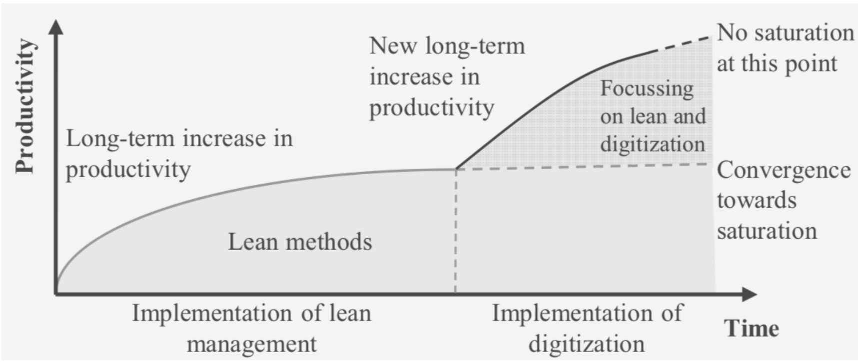
The final level of the CPS 5C model is the Configuration level, which acts as a supervisor for the whole CPS. The fifth level is a feedback level from cyberspace that gives information to the machines and supervises them; This makes the machines able to self-adapt and self-configure. It is a resilience control system (RCS) which applies the improving decisions and counteractive actions to the monitored system, the RCS controls the decisions formed in the cognition level (Bagheri *et al.*, 2015; Ahmadi *et al.*, 2018).

The implementation of CPS is a multistage process that will require a lot of investing, but when done successfully, CPS will offer various advantages for gaining a competitive edge (showcased in table 3).

4.2 Possibilities that Cyber-Physical Systems Bring to Lean Manufacturing

Although Industry 4.0 and Lean share fundamentally different approaches, the goals pursued are the same, increasing added value with minimal costs. The long continuous shift of paradigm towards Lean Manufacturing and following the principles Lean presents has made a significant impact on the development in the Industrial world, both economically and technically. Using Lean companies have been able to lower costs and compete in the global markets drastically, but the increased need to be able to answer quickly to changing customer demands is starting to force into finding ways to increase efficiency even further. Implementing a CPS is unarguably one of the more promising options to obtain efficiency and other benefits. The following figure visualizes the capabilities of Lean methods solely and how digitalization could have an impact on productivity (Monostori, 2014; Prinz, Kreggenfeld and Kuhlenkötter, 2018).

Figure 3. Possible Productivity Changes Using Industry 4.0 Technology



Source of figure: Prinz et al. (2018)

The focus of the following chapters and sub-chapters will be on how the implementation of CPS to production can raise productivity in the long run, as the concrete framework for implementing a CPS is not created yet. When integrating the CPS's into production, the term used is CPPS, which stands for Cyber-Physical Production Systems, which covers the product, the production, and production systems. It has been proposed by Ahmadi *et al.* (2018) the impacts of CPS's in industrial services can lead to seven affordances:

1. Engineering improved equipment with the leverage of data collected
2. Optimization of equipment operations
3. Remote control and management of equipment

4. Predictability to service activities
5. Remote diagnostics and replace field service activities
6. Empower and optimize field service
7. Information and data-driven services

In the following sub-chapters, the analysis will be conducted on the ways how CPS or CPPS can be used the enhance Lean Manufacturing and how could they affect Lean two main pillars, JIT, Jidoka, and the base layer Heijunka and standardized process. These key particles are invented initially as part of the Toyota Production System, one of the best-known examples of Lean models (Liker and Morgan, 2006). According to Sugimori *et al*. (1977) and Liker and Morgan (2006), Just-in-time's main functions enable more efficient inventory balance, diminishes equipment and workforce surplus with efficient material flow, and with the help of Kanban, a production tracker, and controller. Jidoka represents machine and human intelligence and co-operation between each other, the primary function is to diminish and control abnormalities, defectivity, and overproduction. The foundation of (TPS) Lean production is known as Heijunka and standardized process, these stands for overall stability and leveling the manufacturing, leveling enabling the standardization of the process.

4.2.2 Cyber-Physical Systems in Just-in-Time Manufacturing

According to Sugimori *et al.* (1977), Just-in-Time, as a principle, focuses on material flow based on customer demands while minimizing waste and maintaining quality. The purpose of integrating a Cyber-Physical System into a JIT process is to support and enhance the Lean material flow process. Just-in-Time is defined as "Having the right parts and the right amount at the right time." The efficiency and accuracy of a production system can be improved with the usage of CPSs if the particular Lean production system is technologically mature enough.

At the moment, the waste factors are safety stocks, work in progress (WIP), and overproduction. To plan production according to demand, smaller batches have been utilized in order to drive the decline of safety stocks. This above-mentioned leads to production being done according to demand. The Kanban cards, a production scheduling tool, has to be circulated between every station to communicate the required quantities of parts when rebooting the process, and this is not efficient (Wagner, Herrmann and Thiede, 2017).

According to Ohno (1988), Kanban cards originate from Toyota Production Systems Lean methodology. Kanban is a physical paper solely used as a control method for JIT. This piece of paper can be used to inform about pick up or transport information, production information, and help to prevent overproduction and excessive transport. With the implementation of CPS and especially establishing a vertical integration of machine to machine (M2M) connection, it could overwrite the need for Kanban cards throughout the process. The CPS could communicate the quantities of needed parts automatically, and this would also allow more efficient material allocation, stocking, and material consumption. A use case if a Cyber-Physical JIT delivery system was carried out by Wagner, Herrmann and Thiede (2017), which lead to the material flow changing to direct delivery from the central warehouse to the machines cutting out the need of buffers in the shop floor. The material movement would be tracked via sensor networks so that the system is aware of the changes, and the system can keep track of stocks and manufacturing orders — this way, the restocking could be done automatically when inventory levels reach the dynamic minimum. Based on statistical data and comparing it to a digital model of a complete process created by the CPS, the CPS could create a predictive material requirement quantity and automatically place a purchase order. The CPS would improve process reliability and traceability due to the option of removing the shop floors near stocks and diminishing warehousing.

4.2.2 Enhancing Jidoka with Cyber-Physical Systems

Jidoka aims to harmonize humans and machines; the nature of Jidoka thrives for continuous improvement through automation, learning, and abnormality-detection. With CPS's, this could be done even more efficiently. According to Romero *et al.* (2018), resources that CPS's bring, the Jidoka "autonomation" as known as "automation with a human touch" could develop further. After the emergence of Industry 4.0, a possibility for the fourth generation of Jidoka systems have been acknowledged, with the proper use of sensor, controllers and advanced analytics the defect- and abnormality-detection could be performed more accurately, and the detection would be more reliable. The model that Lee, Bagheri and Kao (2015) suggested for CPS's implementation includes a level that links especially to Jidoka's main objectives, the fourth level as known as Cognition level. The level described above connects the machinery and the systems to the experts providing them analytical information. Also, it enables collaborative decision making based on the gathered and analyzed data from the process.

Integration of a Cyber-Physical System and with the use of a CPS, the transformation to an 'autonomative' process can help to enhance the process greatly in many ways. With the assist of CPS- features, such as sensors, the 'autonomative' processes could be perfected progressively with the help of the mutual human-machine learning process (Ansari *et al.*, 2018). Through the CPS enabled cooperation of the automated systems and human operators, the automation of manufacturing environment, facilitation of competent workforce for detecting, eliminating and predicting wrong techniques, operative variants, defects in materials and machine and human errors in manufacturing could be honed and made more accurate (Romero *et al.*, 2019).

Cyber-Physical Systems enable Better Human-Machine interfaces and distribution of information about the process, making the mutual learning process more effective. These enhanced Human-Machine interfaces would allow the translation of process information and results for human operators in various forms such as augmented- or virtual reality. The connecting interfaces would also allow the translation of user inputs into commands for the system, which is one of the factors facilitating the collaborative decision making possible. The CPS could provide extensive and valuable information through the improved IoT, artificial Models, and different computational algorithms using machine learning (Romero *et al*., 2019)

How could the CPS ultimately enhance Jidoka systems from an 'autonomative' viewpoint? The enhanced interfaces enabling the visualization of information and mutual learning would make the learning process of the manufacturing process, its defects, and overall deficits more effective. This enhancement described above would enable the human operators to understand the process better, how it should be maintained, maintenance solutions, and making better troubleshooting decisions. Implementation of modern Jidoka solution using a CPS could help Lean processes effectively reduce waste in the form of diminished defects in the process, allow more automated flexibility, and more effective allocation of resources based on analytics and data gathered from the process. The idea of enhanced Jidoka with an 'autonomative' perspective is to create a sustainable semi-automated and streamlined manufacturing process with enhanced human-machine cooperation through the possibilities of CPS's offer.

4.2.3 Cyber-Physical Systems Usage in Heijunka and Standardized Processes.

The objective of Heijunka is to avoid peaks and lows in production schedules. The term Heijunka stands for leveling the production, and it is a method that converts customer orders into smaller, recurring batches. Kanban cards are used to coordinate the orders at the moment, but Cyber-Physical Systems offer the graphical user interfaces and better data visualization. With the proper implementation of a CPS, the data flow of customer needs and orders could be enhanced, and the leveling could be done more efficiently. Furthermore, digitizing the Heijunka overwrites the need for Kanban cards, and with the proper use of user interfaces, information flows and updating the demand data can be shortened (Ustundag and Cevikcan, 2018).

Cyber-Physical Systems offers a much more efficient data-analysis, due to the data streamlining it offers to Lean Manufacturing. This could be utilized very efficiently in recognizing product groups, product families, and demand indexes based on the data available for the system and the historical data from the system (Żywicki, Rewers and Bożek, 2017). Figure 4. represents the simplified effect of how the Cyber-Physical System enhances Heijunka.

Figure 4. Cyber-Physical System data-analysis effect on Heijunka

Source of the figure: Żywicki, Rewers and Bożek (2017)

The above-shown figure represents how the data-analysis offered by a Cyber-Physical System could enhance the Heijunka. With the CPS mentioned above enhanced data-analysis of the manufacturing, the division to different product groups and product families based on demand indexes and historical data could help the production to be able to recognize the most efficient material allocation to products which have a higher priority based on the demand indexes and offers the highest turnover impact. Furthermore, the upgraded and digitized Heijunka could help to answer to customer pull more efficient, improve the data flow throughout the process and help to allocate resources to economically wise products leveling the production correctly (Żywicki, Rewers and Bożek, 2017).

According to Romero *et al.* (2018), a CPS based Heijunka system could also help with reducing and avoiding passive digital waste. In practice, this implies to the CPS enabled production resource instrumentation in the IoT environment, which supports real-time holistic production scheduling and re-scheduling, leading to avoidance of waste risk creation.

5 Risks and Challenges Affiliated with Industry 4.0 and Cyber-Physical Systems

Although the transformation towards Industry 4.0 manufacturing is becoming very present, there is challenges and risks affiliated with the implementation and initialization that have to be tackled. According to Monostori (2014), the enormous expectations towards Cyber-Physical Systems autonomy, robustness, efficiency, interoperability, and transparency, for example, bring many development related issues. According to He et al. (2016), the Industry 4.0 and IoT enabled Cyber-Physical Systems also face risks and vulnerabilities in the field of cybersecurity, leading to the possible lack of robustness in the systems and being vulnerable towards cybercrime. This section is mostly based on He et al. (2016) *IEEE Congress on Evolutionary Computation (CEC)* whitepaper, discussing the security challenges a CPS could face. The focus of this section is on discovering and presenting significant issues and concerns towards the security of Cyber-Physical Systems, challenges, and difficulties they present, leaving the possible solutions out of the scope.

5.1 The Conservativeness and Lack of Specification Limiting the Implementation of Cyber-Physical Systems

One of the main limiting factors of integrating Cyber-Physical Systems to their maximal potential is the conservative industry of manufacturing. This abovesaid relates to the general operative decisions on tight margins, thus not allowing the strategic uncertainty. Although, there are innovative countries such as Germany, the process of reaching full exploitation of potential will be gradual, for example, through shop-floors without the need for significant investments.

It is generally acknowledged that manufacturing can be facilitated and enhanced by a CPS, but the lack of concrete evidence and framework on how the gaps could be bridged between more or less isolated domains such as embedded systems with IT-systems. Furthermore, connecting those as mentioned above to physical systems opens up the system to cybersecurity problems that will be covered in the next sub-chapter (Wang, Törngren and Onori, 2015).

5.2 Cyber Security Related Challenges and Risks in Manufacturing

As the Cyber-Physical Systems allows centralized control over the process by covering the whole data and information regarding the manufacturing process and connecting it to the human operators, specific weaknesses of the system open for different variants of cyber viruses. Cyber-Physical Systems are offering real-time data and information transferring and management; it is crucial that the data flow is robust and does not get interfered with the process to be efficient (He *et al.*, 2016).

These Advanced manufacturing systems are not as robust and safe as traditional manufacturing systems due to their unique nature and a new way of data transferring inside the process, using Cloud computing and IoT. As a consequence, adequate cybersecurity is a critical factor. Lacks in cybersecurity opens organizations for possible theft of trade-related secrets, intellectual property, damaging alteration to data and disruptions or interruptions to process control. (He *et al.*, 2016).

These cybersecurity issues could threaten the whole supply chain. As Lean Manufacturing infused with a CPS pursues efficient material flow through the supply chain, it enables the connection between the whole supply chain. This factor mentioned above allows the information to be available through the organization leading to possible growth in exposure levels regarding cybersecurity lacks and opening for malware. Security failures in the supply chain could lead to incorrect information flow, reduced material flow, and incorrect availability requirements and data. (He *et al.*, 2016).

6 Discussion and conclusions

This section will assembly and finalize all of the themes presented above and, providing a cogent conclusion on the possibilities and applications that Industry 4.0 and Cyber-Physical Systems could offer. In this section below, will be represented how did the thesis answers the research question and discuss the findings. The latter sub-chapter presents the implications to research and practice, and finally, a presentation of limitations regarding this thesis and the future avenue of these particular topics.

This thesis presented and explored the possibilities that Industry 4.0 and especially Cyber-Physical Systems Could bring into Lean Manufacturing conducted in the form of a literature review, split into three main sections. The first part represents the fundamentals and findings in the literature review of Industry 4.0 and the fundamentals of Cyber-Physical Systems. The second section presents a review of the actual possibilities Cyber-Physical Systems could bring to Lean Manufacturing divided into three sections according to the (TPS) Lean model; possibilities CPS brings to Just-in-Time, Jidoka, and Heijunka. The third part took a critical viewpoint towards the whole concept of CPS implementation and usage, what risks and challenges it brings to Lean Manufacturing.

One of the key findings of this literature review is that Industry 4.0 is heavily linked to Lean Manufacturing and overall having a strong positive correlation with each other. The concepts mentioned above share the same ultimate priorities of waste reduction and efficiency gains. The Cyber-Physical Systems and its information communication technologies offer a wide variety of possibilities to improve different areas of Lean Manufacturing; it could enhance the conception of Lean Manufacturing processes. In Chapter 2, five principles of Lean manufacturing, according to Womack and Jones (1997) is presented, now the effects and enhancement possibilities of a Cyber-Physical System regarding every principle will be presented.

The first principle is identifying customer needs, Cyber-Physical Systems allows more efficient customer data usage it to analyze patterns and market demand more efficiently as presented in the chapter that presents CPS's in Heijunka, as Żywicki, Rewers and Bożek (2017) argued that with the efficient use of customer data, the products within the production, could be divided more efficiently into product groups making the production more efficient according to customer needs, as in allowing more efficient production scheduling.

The second principle is identifying and mapping the value stream, Cyber-Physical systems allow a better mapping of the manufacturing process due to the system covering the whole process and being able to analyze it quantitatively in a digital copy. As the Bagheri *et al.* (2015) 5C model for a Cyber-Physical System proposes, the final level, the configuration level, allows the system to self-adapt and self-configure to optimize and identify the process autonomically. Also, Romero et al. (2019) present that CPS enables the cooperation of humans and systems as known as Jidoka, which allows the automation of manufacturing and facilitation of the workforce to reduce and eliminate waste, also reducing human errors in manufacturing.

The third principle advice to eliminate waste to create flow, the most significant waste creations, according to Wagner, Herrmann and Thiede (2017), are safety stocks and Work-in-progress (WIP). Just-in-time principle emphasizes materials being in the right place at the right time to reduce waste, Cyber-Physical Systems allows better material control throughout the process with big data. With the help of a CPS, the production planning can be done more efficiently, thus allowing smaller batch sizes and the batches being more accurate to demand. This allows the declining of safety stocks. Furthermore, the analysis of the process allows the reduction of WIP in the manner of the system acknowledging the capabilities and knowing the limitations of the production.

The fourth principle is responding to customer pull. This refers to being able to answer to demand and plan the production accordingly. How this principle is enhanced further is with the use of information technologies that CPS offers, it enables the system to recognize pull and plan production according to demand indexes as Żywicki, Rewers and Bożek (2017) stated.

The fifth, the final level, represents the idea of Lean manufacturing pursuing perfection, as in thriving for continuous improvement. For example, Buer, Strandhagen and Chan (2018) argued that Lean Manufacturing is reaching its cap, Industry 4.0 is the answer for this, enabling the possibility of enhancing efficiency, enabling even further streamlining and diminishing waste.

As the main research question was, "How can we enhance Lean principles by utilizing the potential technologies that Industry 4.0 offers?"; this thesis offers a clear answer with linking these principles mentioned above to the new technologies and the possibilities they offer to the five different principles. The analysis of the possibilities is divided according to the main section of the Toyota Production System with the utilization of Cyber-Physical Systems. Thus, this thesis answered also to the second research question, which focused on the utilization of Cyber-Physical Systems.

What was surprising is that Industry 4.0 does not necessarily offer any new “hard” production methods to Lean Manufacturing. However, the information technologies embedded in Cyber-Physical System allow a higher level of streamlining, and the more efficient data usage allows higher efficiency, and based on the data the production could just be rearranged to be more efficient.

The results of this thesis indicate that Industry 4.0 and Cyber-Physical Systems most definitely can offer great value to Lean Manufacturing and enhance it up to a new level of efficiency, making processes more sustainable in the way of waste reduction. The analysis of the possible implementations of Cyber-Physical Systems into Lean resulted in promising opportunities. CPS, all in all, is a very applicable concept to Lean Manufacturing as it brings waste and deficit reduction and could help to streamline the processes when executed correctly.

6.1 Implications for research and practice

The results are very corroborative to the previous researches and their findings, this thesis uses a lot of general information regarding Industry 4.0 and Cyber-Physical Systems and embeds them to Lean Manufacturing and its principles. The results were expected to be quite similar to the previous literature because this thesis does not necessarily provide new information; it just connects these different concepts in a reasoned manner. Nevertheless, this thesis still provides a thorough justification of why these two concepts are connected and helps to understand why these concepts synergize together. This thesis might also help to lay the base ground for the connection between Lean Manufacturing and Industry 4.0 because there are no existing theories about how these concepts mentioned above should be approached together.

Industry 4.0 will affect companies' dynamics between the worker and the machinery, as companies start to move towards Industry 4.0 technology solutions. The modern solutions, for example, a Cyber-Physical Systems, will require a higher understanding of the operative side and how the systems work, to be able to operate and manage the systems. Also, the probability is that most of the companies adapting to the use of Industry 4.0 technologies will be the larger companies due to implementation requiring a lot of capital. So, these technologies will probably be unreachable for smaller businesses for quite a while.

6.2 Limitations and Future Research

The constricted scope and restricted available information regarding this thesis lead to some closely related parts or significant associations connected to this subject being left without attention. Nevertheless, as a topic Industry 4.0 evolves at a swift pace and nonlinearly, resulting in sources becoming outdated as new evidence is proven. Particularly up-to-date empirical and statistical data on the effects off Industry 4.0 and Cyber-Physical Systems on Lean Manufacturing would provide support regarding research on this topic. Also, the lack of articles and especially lack of concrete applications regarding usage of CPS in Lean Manufacturing restricted presenting extensive evidence of how would the CPS impact Lean Manufacturing in practice.

As stated in the discussion part, the diverse and novel nature Industry 4.0 and Cyber-Physical Systems offer a great variety of ways to approach the research, which means a vast spectrum of different research aspects. This said it is crucial to keep researching Industry 4.0 as a topic to be able to harvest the benefits it presents.

Hopefully, this research paper, alongside other studies, results in an applicable framework to use in the future. Other questions that could be considered in the future:

1. Will there be latency related issues, and how could they affect the interconnection of the Cyber-Physical System?
2. How could cybersecurity-related issues be solved within the Cyber-Physical Systems?

3. How will the implementation of a CPS effect on humans' positions in organizations?

Furthermore, a suggestion is that the link between Cyber-Physical Systems and Lean Manufacturing because of the proven positive correlation with each other, it should be researched more. The sincere desire is that this thesis can be used as a foundation for future research and display the importance of this topic.

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