Industrial Production Philosophies

Sepehr Mohammadi*

Department of Civil and Industrial Engineering, Uppsala University, Uppsala, Sweden
***Corresponding author**: sep@vt.edu

Abstract
This article discusses how Lean, SixSigma, and Theory of Constraints, three of today's most popular production philosophies, were founded on the principles of Scientific Management (Taylorism). The mechanism that each of these various production philosophies employs to promote a continuous improvement operation strategy, as well as the growth of industry 4.0 in this effort to create the production system of the future.
To study the industrial production philosophies comprehensively, this article first addresses important milestones in the development of industrial production systems and describes today's prominent production philosophies, as well as their similarities and differences. Later, the influence of industry 4.0 on developing industrial production systems will be explained and elaborated.
Furthermore, the article explains how production philosophies can contribute to more effective use of advanced data analysis, simulation, and optimization, as influential tools to implement a production philosophy into a production system successfully.

Keywords
Production Philosophies, Lean, SixSigma, Theory of Constraints, Scientific Management, Data Analysis, Simulation, Optimization
Word Count: 3987

Contents

1. Introduction

1.1 Definition of Production Philosophy

Philosophy is a difficult subject to define in large part. But for at least one controversial definition of philosophy, the relation between the sciences-physical, biological, social, and behavioral-and philosophy are so close that philosophy of a science must be a central concern of both philosophers and scientists. On this definition, philosophy deals initially with the questions the sciences cannot yet or perhaps can never answer, and with the further questions of why the sciences cannot answer these questions.[19]

Production is a fundamental societal and economic activity. Production has to do with the transformation of raw materials into useful objects and includes the knowledge to complete the transformation effectively. Thus, production is a board topic ranging from philosophies about how to approach production such as lean and quick response manufacturing, how to organize production facilities, how to analyze production operations, how to control the flow of materials during production, the devices used to move materials within a facility, and strategies for coordinating multiple production facilities. [21]

To simplify the definition of production philosophy, we refer to it as beliefs that contribute to solving production problems that used to be vague and unanswered before coming up with the specific perspective contributing to the philosophy.On the other hand, a method is a structured procedure for bringing about a certain goal. The term methodology refers to the methods themselves or to the philosophical discussion of associated background assumptions. Therefore, we can also assume production philosophies as production methodologies, as the border between the two concepts is not apparent from some perspectives.

1.2 Industrial Revolutions

Throughout history, there have been several breakthroughs that all have been shown by changes in the type of technological mode as a result of mass implementation of accumulated industrial innovations and systemic transformations in industry, which results in deep changes in logistics and manufactured products. These breakthroughs are commonly called industrial revolutions.

1.2.1 1st Industrial Revolution

The First Industrial Revolution began in the 18th century through the use of steam power and mechanisation of production. Steam power was already known. The use of it for industrial purposes was the greatest breakthrough for increasing human productivity. Instead of weaving looms powered by muscle, steam-engines could be used for power. Developments such as the steamship or the steam-powered locomotive brought about further massive changes because humans and goods could move great distances in fewer hours.[9]

1.2.2 2nd Industrial Revolution

The Second Industrial Revolution began in the 19th century through the discovery of electricity and assembly line production. A milestone of Industry 2.0 was Frederick Taylor's The Principle of Scientific Management, which was the first publication on modern management theory. Taylor is considered the 'Father of Management'. The demand during Industry 2.0 had two dimensions – volume and variety. We can call this demand environment as Stable Market. Two innovators, Henry Ford and Taiichi Ohno, practiced and extended Taylor's theory. Ford addressed the shortage of supply in product volumes using mass production assembly lines. Ohno addressed various customer interests in product varieties by developing the Toyota production system (TPS), the precursor to lean.[27]

1.2.3 3rd Industrial Revolution

The third revolution brought forth the rise of electronics, telecommunications and, of course, computers. The third industrial revolution opened the doors to space expeditions, research, and biotechnology through the new technologies. In the world of the industries, two major inventions, Programmable Logic Controllers (PLCs) and Robots, helped give rise to an era of high-level automation.[27]

1.2.4 4th Industrial Revolution

The Fourth Industrial Revolution is characterised by the application of information and communication technologies to industry and is also known as "Industry 4.0". Production systems that already have computer technology are expanded by a network connection and have a digital twin on the Internet so to speak. [27] The influence of Industry 4.0 is discussed more later in this article.

At the ten-year mark of the introduction of Industry 4.0, the European Commission announced Industry 5.0. Industry 4.0 is considered to be technology-driven, whereas Industry 5.0 is value-driven. The co-existence of two Industrial Revolutions invites questions and hence demands discussions and clarifications. [26] Later in this article, we will discuss the emergence of Industry 5.0 and its differences from Industry 4.0

1.3 Development of Production Systems

Production systems have always been a significant part of the industry throughout history. Therefore, production systems have developed alongside the industry, contributing to the construction of different production philosophies, each of which is considered a breakthrough pushing humans' knowledge forward to reach where we are now. After the emergence of the Toyota Production System (TPS) on the basis of Taylor's

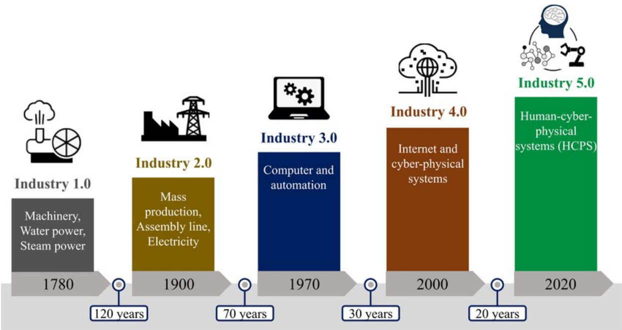

Figure 1. Industrial Revolutions [4]

Scientific Management, Theory of Constraint (TOC) and SixSigma can be named as the major production developments introduced in the 80s.

By the end of 20th century, businesses were competing increasingly on time and quality. Companies couldn't survive if they fail to obtain competitive advantages by producing high quality products and services in shorter throughput time and quicker inventory turnover, adjusting to the production philosophies.

Later on in the Industry 4.0, tools and technologies were devised to better adjust production systems with production philosophies and increase their efficacy.

1.4 Objectives

For-profit organizations exist for two purposes: to make money now and to make money in the future. Making money now requires organizations to relentlessly remove needless sources of waste and variation so that their products and services are not only profitable but are also consistently delivered on time and at the right price.[20]

But to sustain these profits (that is, to make money in the future), organizations must continually reinvent themselves. What worked yesterday and today probably will not work tomorrow or next year, so change is necessary. The good news is that it is much easier to manage change than it is to react to it. Because products or services have such short half-lives these days, change must not only be expected, but also be passionately pursued and embraced.[20] But what is it that you should be changing? What is the methodology or the philosophy? How to implement the improvement? What tools to be utilized? These are the question we are going to answer in this article.

Knowing what to change, what to change to, and how to implement change are the determining factors for how successful an organization will be in the future. In an endeavour to tackle this question we are going to study The mechanism that these different production philosophies use to support an operation strategy of continuous improvement and how industry 4.0 takes off in this endeavor to develop the production system of the future.

1.5 Methods

This article is a final report of the Industrial Production Philosophies course and aims to overview the course learnings and follow up with some discussions.The course contained three main sourcebooks as stated below, in addition to four lectures from the teacher and guest lecturers, as well as nine student group presentations and class discussions during the seminars. The source books are: [23], [17], [7]

2. Prominent Production Philosophies

Twenty-first century manufacturing is characterized by customized products. This has led to the complex production planning and control systems making mass production To overcome this situation and to become more profitable, many manufacturers, particularly automotive organizations, turned to "lean manufacturing" (LM), "Theory of Constraint" (TOC), and "SixSigma" as today's prominent production and manufacturing philosophies.

2.1 Lean Manufacturing

The concept of lean manufacturing was developed for maximizing the resource utilization through minimization of waste, later on lean was formulated in response to the fluctuating and competitive business environment. Due to rapidly changing business environment the organizations are forced to face challenges and complexities. Any organization whether manufacturing or service oriented to survive may ultimately depend on its ability to systematically and continuously respond to these changes for enhancing the product value. Therefore value adding process is necessary to achieve this perfection; hence implementing a lean manufacturing system is becoming a core competency for any type of organizations to sustain.[22]

2.1.1 Background

The lean concept originated in Japan after the second world war when Japanese manufacturers realized that they could not afford the massive investment required to rebuild devastated facilities. Toyota produced automobiles with lesser inventory, human effort, investment, and defects and introduced a greater and ever growing variety of products.[2]

2.1.2 Lean Structure

Lean manufacturing is the name given to a team-based systematic approach for discovering and eliminating various types of waste. There are various tools which are effectively used for elimination of wastes in the organization. These tools include just-in-time, value stream mapping (VSM), kaizen, material requirement planning, kanban, 5s, etc.[8]

1. Just-In-Time (JIT): The principles of Just-In-Time are that the right part should be at the right place at the right amount at the right time. To make sure production can move without interruption.[17]

2. Value Stream Mapping (VSM): VSM is a world-famous graphical tool which helps to enlighten and analyse the work-flow and to find the valueadded and non-value-added activities contributing to the final product.[8]

3. Kaizen: Kaizen is a Japanese term which is used for continuous improvement; the continuing involvment of everyone – whether managers or employees.[8]

4. Material Requirement Planning (MRP):MRP is a powerful tool that converts the requirements for end products into a detailed schedule of raw materials.[8]

5. Kanban: Kanban is a simple parts-movement system in which material movement between workstations in a production line is based on cards. [8]

6. Jidoka: Jidoka highlights the causes of problems because work stops immediately when a problem first occurs.[17]

7. 5s: 5S is a methodology for sorting, organizing, cleaning, standardizing and sustaining a productive work environment.[8]

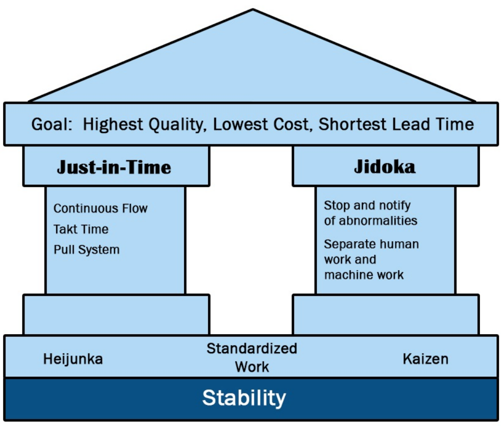

Figure 2. Basic lean concepts and methods.

2.1.3 Steps of lean manufacturing implementation

1. Identification of wastes, their type, and their cause in the system.

2. Treating the causes and curing the problems permanently.

3. Identify the effects of the solution on the entire system.

4. Realize that sustainable improvement

2.1.4 Continuous Improvement

Lean thinkers are aiming for 'perfection' and in doing so the improvement cycle is never ending. For many in the process industries this culture change is the hardest change of all. However, for assured sustainability the organizations who are truly lean will invest the time and effort to support a change in culture—the way we do things around here.[12]

2.2 Theory of Constraint (TOC)

A new approach to the management of production and operations was developed by Goldratt in the form of a novel in the late 1970s. Now known as the theory of constraints (TOC), it provides a coherent management theory for running an organisation. It has two major components: a philosophy which underpins the working principle of on-going improvement, and a generic approach for investigating, analysing and creating solutions to problems called the "thinking process" (TP).[18]

2.2.1 New performance measurements

TOC assumes that the goal of an organisation is to make money both now and in the future. To measure an organisation's performance in achieving this goal, two sets of measurements have been prescribed by Goldratt and Fox [7] : global (financial) measurements and operational measurement. Since global measurements (Net Profit, ROI and Cash Flow) can be expressed through the operational measurements, operational measurements are defined first.

1. Throughput (T): the rate at which the system generates money through sales (output which is not sold is not throughput but inventory).[7]

2. Inventory (I): all the money invested in things the system intends to sell.[7]

3. Operating expense (OE): all the money the system spends in turning inventory into throughput.[7]

2.2.2 The Concept

The concept of the TOC can be summarised as:

1. Every system must have at least one constraint. If it were not true, then a real system such as a profit making organisation would make unlimited profit. [7] Each part of a system is whether a bottleneck defining a constraint or non-bottleneck.

2. The existence of constraints represents opportunities for improvement. Contrary to conventional thinking, TOC views constraints as positive, not negative. Because constraints determine the performance of a system, a gradual elevation of the system's constraints will improve its performance.[7]

The TOC has two major components.These components are discussed in the following sub-sections.

2.2.3 The Philosophy

The working principle of TOC provides a focus for a continuous improvement process. The principle consists of five focusing steps:

1. Identify the system's constraint(s).

2. Decide how to exploit the system's constraint(s).

3. Subordinate everything else to the above decision.

4. Elevate the system's constraint(s).

5. If in any of the previous steps a constraint is broken, go back to step 1.

2.2.4 Thinking Process

Recently, Goldratt (1994) developed a generic approach to address policy constraints and create breakthrough solutions for them using common sense, intuitive knowledge and logic. This procedure is referred to as the thinking process (TP). According to Goldratt, while dealing with constraints managers are required to make three generic decisions. [18] These are:

1. Decide what to change.

2. Decide what to change to.

3. Decide how to cause the change.

2.3 SixSigma

The six sigma method is a project-driven management approach to improve the organization's products, services, and processes by continually reducing defects in the organization. It is a business strategy that focuses on improving customer requirements understanding, business systems, productivity, and financial performance. Dating back to the mid 1980s, applications of the six sigma methods allowed many organizations to sustain their competitive advantage by integrating their knowledge of the process with statistics, engineering, and project management [10]

2.3.1 SixSigma Project Management Method

DMAIC, an acronym for Define, Measure, Analyze, Improve, and Control, is a structured problem-solving procedure widely used in quality and process improvement. [15] DMAIC is explained as in table 1

Six Sigma Steps	Key Concepts
Define	Define the requirements and expectations of the customer Define the project boundaries Define the process by mapping the business flow
Measure	Measure the process to satisfy customer's needs Develop a data collection plan Collect and compare data to determine issues and shortfalls
Analyze	Analyze the causes of defects and sources of variation Determine the variations in the process Prioritize opportunities for future improvement
Improve	Improve the process to eliminate variations Develop creative alternatives and implement enhanced plan
Control	Control process variations to meet customer requirements Develop a strategy to monitor and control the improved process Implement the improvements of systems and structures

Table 1. Key steps of six sigma using DMAIC process

2.4 Comparing Philosophies

To compare today's prominent philosophies, it should be considered that all are based on the scientific management theory introduced by Taylor, stating that every aspect of the managerial and operational division in the firm or organization should work toward increasing efficiency. On this basis, each production philosophy considers some objectives and methods to achieve them that contribute to a different definition of efficacy and profitability for different philosophies while all are working toward the same goal, which is to stay competitive in the market through an efficient use of processes and resources combined with a continuous improvement.

To identify the relationship between the primary theory and the primary focus of the tools and methodology, this if/then type of relationship for each philosophy can be proposed: [16]

- For lean: “If we focus on waste removal, then flow time will improve.”
- For TOC: “If we focus on constraints, then throughput volume will improve.”
- For Six Sigma: “If we focus on reducing variation, then we will have more uniform process output.”

	Lean Manufacturing	Theory of Constraint	Six Sigma
Theory Focus	Remove waste Flow focused	Manage constraints System constraints	Reduce variation Problem focused
Primary Effect	Reduced flow time	Fast throughput	Uniform process output
Secondary Effect	Less variation. Uniform output Less inventory Improved quality	Less waste Less inventory Improved quality	Less waste less inventory Fast throughput Improved quality

Table 2. Comparison of Production Philosophies

In table 2 it explained that each improvement methodology appears to be driving toward common tools and concepts. However, different methodologies begin the journey from different perspectives. At the secondary effects level of the model, the results from each methodology start to look similar. Many of the secondary effects of one methodology look similar to the primary effect or focus of another methodology.

2.4.1 Selecting the suitable Philosophy

Selection of a process improvement methodology is dependent on the culture of your organization. If many popular programs appear to end up in the same place addressing the same issues after a number of years of use, the main issue left to explore is the speed at which a method will be accepted into an organization:[16]

- If the organization values analytical studies and the relationships of data, charts and analysis, Six Sigma is a perfect program for you to start with.
- If the organization values visual change and right now time, then lean thinking might be the way to go.
- If the organization values a systems approach where total participation is not desired and if it values the separation between worker and management, then TOC might be a good way to start.

3. New Era in the Production Systems

By the start of 21st century, bringing progressive globalisation, mass customisation and competitive business environments stated that traditional production is facing new business challenges in the turbulent economy. In such a situation, new technologies are arising leading to a more sustainable production system.

3.1 Influence of Industry 4.0

Industry 4.0 is considered a comprehensive set of emerging technologies that establish a new industrial production perspective based on digital solutions. Leading base technologies introduced in Industry 4.0 are stated below:

- Internet of Things(IoT)
- Cyber-Physical Systems(CPS)
- Big Data and Analytics/Artificial Intelligence (BDA/AI)
- Cloud technology/computing

Smart manufacturing is at the core of the Industry 4.0 concept. Smart Production Systems (SPS) are production systems capable of autonomously diagnosing their health and autonomously designing optimal continuous improvement projects, leading to the desired productivity improvement. [1]

3.1.1 A conceptual framework for Industry 4.0 technologies

To elaborate on the structure of the application of Industry 4.0, besides the base technologies mentioned above, front-end technologies are introduced below:

- Smart Manufacturing: The transformation of the manufacturing activities based on emerging technologies
- Smart Product: The way product are offered based on emerging technologies
- Smart Supply Chain: The way raw materials and product are delivered
- Smart Working: The new ways workers perform their activities based on the support of emerging technologies

As pictured in figure 3, the base and front-end technologies of Industry 4.0 work together to increase the competitiveness of the firm or organization. In other words, Industry 4.0 has provided production systems

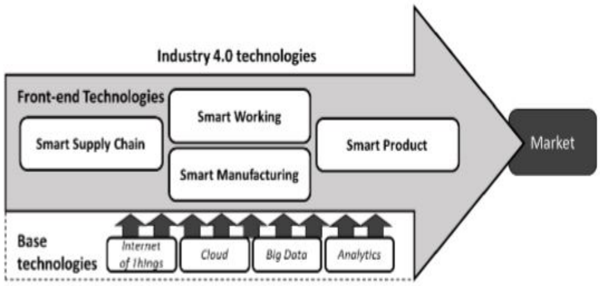

Figure 3. Theoretical framework of Industry 4.0 technologies.[5]

with new tools to serve their philosophies more efficiently. This comes with more complexity that requires strategic management to adopt the company's goals with Industry 4.0, which requires committed leadership, fundamental resource allocation, and a modern managerial system.

The variety of tools, technologies, and data has given rise to the emergence of complex systems in today's production environment. As a result, implementing production philosophies is not as straightforward as in the past. Data analysis, simulation, and optimization are the main approaches utilized to assist the successful implementation of production philosophies. In the following sections, these topics will be explained and discussed.

3.2 Data Analysis

Data-analysis is defined as advanced analytic techniques that operate on a large database with the goal of discovering useful information, informing conclusions, and supporting decision-making.

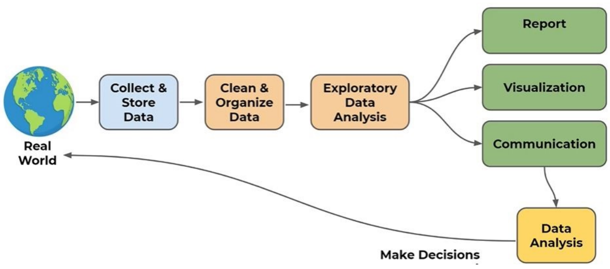

Figure 4. Data Analysis Conceptual Framework

Companies adopt continuous improvement programs at every stage to eliminate waste, manage constraints, and increase efficiency through data scientific approaches resulting in improved competitiveness. Therefore, four main applications for data analysis in production systems are considered:

1. Demand, Supply Chain and Price Analysis
2. Analysis of Warranty Claims
3. Predictive Maintenance Program
4. Process and Production Improvement

As the first two applications are widely discussed in various sectors, this article aims to elaborate on the others.

3.2.1 Predictive Maintenance Program

Data scientists use data from a variety of sensors and track that data against the optimal reading to determine if a piece of machinery is about to fail [28].The data scientist interprets that data through predictive modeling. These models determine whether the machine is about to have a breakdown and what action you should take to manage it most effectively.

Contrasting this with reactive maintenance, where maintenance activity takes place after the disruption has occurred, or scheduled maintenance, where plants follow a predetermined inspection and repair schedule, regardless of how the machine is performing, it will be realised how the predictive maintenance contribute to elimination of waste as well as reducing the downtime of machines.

3.2.2 Process and Production Improvement

Key Performance Indicator (KPI) is a strong signal for evaluating the efficiency and productivity levels. With a growing number of sensors implemented in manufacturing systems a large amount of data is generated. Among manufacturing companies only 5.5 percent of the available database is used for process optimization applying data-analytics. This low rate is mainly because of [24]:

- Lack of Transparency
- Limited Data access and hardship to assess the problem-specific Data
- Missing product Data information
- Financial expenditures and organizational barriers to make a change

Therefore, production engineers have to estimate which additionally gathered data could potentially contribute to the intended process optimization before changing the production equipment or resources. As a result, in order to apply a practical advanced data analysis, we need to have a well-defined relationship between the improvement objectives and provided data, which is not reachable unless we implement production philosophies.

3.3 Simulation

Today, modelling and simulation is a standard process in system development, e.g. to support design tasks or to validate system properties.In this sense, simulation merges the physical and virtual world in all life cycle phases [3]. simulation is a model that mimics the operation of an existing or proposed system, providing evidence for decision-making by being able to test different scenarios or process changes.

3.3.1 Simulation-based decision support

yber-physical production systems (CPPS), the backbone of Industry 4.0, enable flexible and adaptive manufacturing of customized products through the integration and connection of cyber-physical systems (CPS)[14]. Connecting such a digital model to a real material handling system in order to derive simulation-based decision support leads to the concept of digital twins [6] The objective of a digital twin within a manufacturing system is to facilitate decision-making processes and to enable decision automation through simulation of certain elements and processes within the real system.

3.3.2 Implementing Philosophies through Simulation

Simulation can offer a systemic view and provide the analysis of how different changes in one component affect the system[25]. It is a better tool for identifying where and how to improve the system. It can help to explore, discuss and re-test scenarios that are non-intuitive or nonexisting and probably would have been very difficult or impossible to find without simulation[13]. Through simulation, one can find bottlenecks and break them to implement the Theory of Constraint or can handle variation and work with probability distributions to reduce waste and implement Lean.

Moreover, due to varying routes and high variance of workpieces, material flows in cyber-physical production systems can get highly complex. Therefore, to utilize simulation effectively, production philosophies must be considered as the central concept defining the objectives of the improvement system so the structure of the manufacturing system can be simplified based on that.

3.4 Optimization

Optimization is not a new concept and has been widely used, especially since the emergence of Scientific Management by Taylor, who came up with the theory of increasing efficiency in the firm or organization as much as possible. But nowadays, alongside all the digital breakthroughs, optimization can utilize much more sophisticated infrastructures and tools.

3.4.1 Optimization in Production Systems

Optimization has many definitions based on the situation, but in general, it can be referred to as An act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible. Optimization can be considered as the complement of every other tool when it comes to making a decision, as it tackles the dilemma of trade-offs to find the optimal or nearly optimal solution. Therefore, to implement production philosophies, optimization is a mandatory tool to satisfy the objectives of each philosophy in the scale of the organization.

3.4.2 Simulation-Based Optimization

The shortcoming of both lean and simulation is that they usually need a large amount of time in order to achieve an optimal configuration and still optimality is not guaranteed. Since lean and simulation are not optimization tools by themselves, it seems that to include optimization would provide a better process and therefore, a better outcome. Combining optimization and simulation tools allows decision-makers to quickly determine optimal (or nearly optimal) system configurations, even for complex integrated facilities. Consequently, the integration of optimization together with simulation is necessary if the optimal range of solutions for the given input is wanted. Moreover, if there are multiple objectives to be analyzed at the same time, then Simulation-based Multi-objective Optimization (SMO) is the preferred approach. SMO facilitates the search for trade-offs solutions between several conflicting objectives. [25]

3.4.3 Data-Based Optimization

Following the topic explained in the application of Data analysis to improve the processes and production in the section 3.2.2, optimization is the tool that overcomes the barriers in this sector by defining the target KPI according to the objectives of the improvement as well as the related data to the target KPI.

As the priorities are different from different perspectives, there would be various optimal solutions in a system. Therefore, to apply optimization effectively in a production system, there should first be a production philosophy defining objectives and priorities.

3.5 Industry 5.0; The Future

Based on the observations from several state-of-the-art, Industry 5.0 is already in practice in several sectors like healthcare, cloud manufacturing, supply chain management, manufacturing/production, education, human–cyber–physical-systems, disaster management, etc. [11]

In Industry 5.0, the human role is back in a different way than it was in the past. The human-computer interaction is the core of Industry 5.0, and humans make decisions through tools such as Augmented Reality(AR) and Virtual Reality(VR). Therefore, he human–robot co-working ability of Industry 5.0 utilizes the intelligence and decision making of humans, supported by key-enabling technologies, helps in achieving mass personalization.

Industry 5.0 is a concept that has been designed to harmonize the working space and efficiency of humans and machines in a consistent manner. Enabled by a variety of emerging applications and supporting technologies, Industry 5.0 is expected to increase manufacturing production and customer satisfaction. We also presented a number of challenges and open issues like security, privacy, human–robot co-working in a factory, scalability, and skilled workforce that should be handled to better realize the concept of Industry 5.0 in the near future. [11]

4. Discussion

In this article, we first had an overview of the industrial revolutions to define the path that has taken us to the present state of the production systems. To answer the questions regarding the continuous improvements of production firms and organizations, we described the most prominent production philosophies used today and discussed why it is necessary for companies to implement a philosophy not only to be profitable in the present time but also to stay profitable in the future. Later on, we elaborated on the influences of Industry 4.0 as a digital breakthrough as well as the tools and knowledge required to adapt to these changes. We introduced Data analysis, simulation, and optimization as the most dominant tools for successfully implementing production philosophies. Industry 5.0 is also presented in a nutshell in this article as the latest industrial revolution that brings up new technologies, tools, and above all, changes that production systems should start to be prepared for and tackle its challenges based on their philosophy.

5. Conclusions

Production philosophies are the beliefs that assign meaning to every part of a production structure because they define the primary objectives of the system and the procedure required to follow in order to accomplish goals. Therefore, an inseparable soul of every production system is the philosophy behind that, which can be one or a combination of the philosophies presented in this article.

Nowadays, many technologies are provided that can be utilized to implement production philosophies in the production systems successfully. The key to continuous improvement is to passionately pursue and embrace the new changes that come with new technologies. Moreover, we should keep in mind that these tools and technologies can't be effective unless they serve a philosophy with predefined objectives and procedures.

References

[1] P. Alavian et al. "Smart production systems: automating decision-making in manufacturing environment". In: *International Journal of Production Research* 58.3 (2020), pp. 828–845. DOI: 10.1080/00207543.2019.1600765. eprint: https://doi.org/10.1080/00207543.2019.1600765.

[2] J. Bhamu and K. Singh Sangwan. "Lean manufacturing: literature review and research issues". In: (2014). DOI: https://doi.org/10.1108/IJOPM-08-2012-0315.

[3] S. Boschert and R. Rosen. "Digital twin—the simulation aspect". In: *Mechatronic futures*. Springer, 2016, pp. 59–74.

[4] X. Chen et al. "A human-cyber-physical system toward intelligent wind turbine operation and maintenance". In: *Sustainability* 13.2 (2021), p. 561.

[5] A. G. Frank, L. S. Dalenogare, and N. F. Ayala. "Industry 4.0 technologies: Implementation patterns in manufacturing companies". In: *International Journal of Production Economics* 210 (2019), pp. 15–26. ISSN: 0925-5273. DOI: https://doi.org/10.1016/j.ijpe.2019.01.004.

[6] M. Glatt et al. "Modeling and implementation of a digital twin of material flows based on physics simulation". In: *Journal of Manufacturing Systems* 58 (2021). Digital Twin towards Smart Manufacturing and Industry 4.0, pp. 231–245. ISSN: 0278-6125. DOI: https://doi.org/10.1016/j.jmsy.2020.04.015.

[7] J. Goldratt Eliyahu M.; Cox. "The goal: a process of ongoing improvement." In: (1998).

[8] S. Gupta and S. K. Jain. "A literature review of lean manufacturing". In: *International Journal of Management Science and Engineering Management* 8.4 (2013), pp. 241–249. DOI: 10.1080/17509653.2013.825074.

[9] C. Hirschman and E. Mogford. "Immigration and the American industrial revolution from 1880 to 1920". In: *Social Science Research* 38.4 (2009), pp. 897–920. ISSN: 0049-089X. DOI: https://doi.org/10.1016/j.ssresearch.2009.04.001.

[10] Y. H. Kwak and F. T. Anbari. "Benefits, obstacles, and future of six sigma approach". In: *Technovation* 26.5 (2006), pp. 708–715. ISSN: 0166-4972. DOI: https://doi.org/10.1016/j.technovation.2004.10.003.

[11] P. K. R. Maddikunta et al. "Industry 5.0: A survey on enabling technologies and potential applications". In: *Journal of Industrial Information Integration* 26 (2022), p. 100257. ISSN: 2452-414X. DOI: https://doi.org/10.1016/j.jii.2021.100257.

[12] T. Melton. "The Benefits of Lean Manufacturing: What Lean Thinking has to Offer the Process Industries". In: *Chemical Engineering Research and Design* 83.6 (2005). 7th World Congress of Chemical Engineering, pp. 662–673. ISSN: 0263-8762. DOI: https://doi.org/10.1205/cherd.04351.

[13] G. Miller, J. Pawloski, and C. R. Standridge. "A case study of lean, sustainable manufacturing". In: *Journal of Industrial Engineering and Management (JIEM)* 3.1 (2010), pp. 11–32.

[14] L. Monostori et al. "Cyber-physical systems in manufacturing". In: *CIRP Annals* 65.2 (2016), pp. 621–641. ISSN: 0007-8506. DOI: https://doi.org/10.1016/j.cirp.2016.06.005.

[15] D. C. Montgomery and W. H. Woodall. "An Overview of Six Sigma". In: *International Statistical Review / Revue Internationale de Statistique* 76.3 (2008), pp. 329–346. ISSN: 03067734, 17515823. (Visited on 10/19/2022).

[16] D. Nave. "How to compare six sigma, lean and the theory of constraints". In: *Quality progress* 35.3 (2002), pp. 73–80.

[17] T. Ohno. "oyota production system: be- yond large-scale production." In: (1998).

[18] S. Rahman. "Theory of constraints: A review of the philosophy and its applications". In: (1998). DOI: https://doi.org/10.1108/01443579810199720.

[19] A. Rosenberg. "Philosophy of Science: A Contemporary Introduction (3rd ed.)." In: (2011). DOI: https://doi.org/10.4324/9780203807514.

[20] B. Sproull. "The Ultimate Improvement Cycle: Maximizing Profits through the Integration of Lean, Six Sigma, and the Theory of Constraints". In: (2009). DOI: https://doi.org/10.4324/9780367802912.

[21] C. R. Standridge. "Introduction to production: philosophies, flow, and analysis". In: (2019).

[22] R. Sundar, A. Balaji, and R. S. Kumar. "A Review on Lean Manufacturing Implementation Techniques". In: *Procedia Engineering* 97 (2014). "12th Global Congress on Manufacturing and Management" GCMM - 2014, pp. 1875–1885. ISSN: 1877-7058. DOI: https://doi.org/10.1016/j.proeng.2014.12.341.

[23] F. W. Taylor. "The principles of scientific management. Stilwell, KS: Digireads, c2008". In: (2008).

[24] F. Ungermann et al. "Data analytics for manufacturing systems–a data-driven approach for process optimization". In: *Procedia CIRP* 81 (2019), pp. 369–374.

[25] A. G. Uriarte et al. "Lean, simulation and optimization: A win-win combination". In: *2015 Winter Simulation Conference (WSC)*. 2015, pp. 2227–2238. DOI: 10.1109/WSC.2015.7408335.

[26] X. Xu et al. "Industry 4.0 and Industry 5.0—Inception, conception and perception". In: *Journal of Manufacturing Systems* 61 (2021), pp. 530–535. ISSN: 0278-6125. DOI: https://doi.org/10.1016/j.jmsy.2021.10.006.

[27] Y. Yin, K. E. Stecke, and D. Li. "The evolution of production systems from Industry 2.0 through Industry 4.0". In: *International Journal of Production Research* 56.1-2 (2018), pp. 848–861.

[28] T. Zonta et al. "Predictive maintenance in the Industry 4.0: A systematic literature review". In: *Computers Industrial Engineering* 150 (2020), p. 106889. ISSN: 0360-8352. DOI: https://doi.org/10.1016/j.cie.2020.106889.

6. Self Assessment Table

Criteria	Address
Summarize important milestones in the development of industrial production systems	Section 1.2 Section 1.3
Describe today's prominent production philosophies	Section 2
Distinguish and contrast similarities and differences between today's prominent production philosophies	Section 2.4
Explain the influence of Industry 4.0 on the development of industrial production systems	Section 3.1
Explain and elaborate on how advanced data analysis, simulation and optimization tools can contribute to a successful implementation of production philosophies in a business/production system	Section 3.2 Section 3.3 Section 3.4
Explain and elaborate on how production philosophies can contribute to more effective use of advanced data analysis, simulation and optimization tools	Last paragraph of: Section 3.2 Section 3.3 Section 3.4
Discussion	Section 4
Conclusion	Section 5

Table 3. Self Assessment Table