Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 107 (2022) 202–208

www.elsevier.com/locate/procedia

55th CIRP Conference on Manufacturing Systems

Implications of Lean 4.0 Methods on Relevant Target Dimensions: Time, Cost, Quality, Employee Involvement, and Flexibility

Fabian Dillinger*, Julia Bergermeier, Gunther Reinhart

Technical University of Munich, Institute for Machine Tools and Industrial Management (iwb)
Boltzmannstrasse 15, 85748 Garching, Germany

* Corresponding author. Tel.: +49-(0)89-289-15575; fax: +49-(0)89-289-15555. *E-mail address:* fabian.dillinger@iwb.tum.de

Abstract

Industry 4.0 is expected to provide a framework for coping with the increasing market dynamics and complexity in the highly competitive manufacturing industry. As the holistic approach of Lean Production has been applied in many industries as a standard for several decades, the interdependency of Lean Production and Industry 4.0 plays a crucial role. Thus, combining both paradigms into one integrated approach, commonly known as Lean 4.0, is of high topicality in the academic and industrial environment. However, the effects on target dimensions of Lean 4.0 in a manufacturing system remain unclear. In this scientific contribution, an impact analysis is conducted to measure the implications of Lean 4.0 on relevant target dimensions. The intention is to unhide relevant impacts and support manufacturers' decision-making for reaching aspired objectives. Lean 4.0 use cases are created based on existing literature to assess concrete Lean 4.0 scenarios concerning the identified target dimensions. In expert interviews, following the Delphi study method, the relevant data is collected, in which the participants assess the implications of the use cases on the target dimension. The results show that the implications can highly differentiate depending on the applied Lean Production method and Industry 4.0 technologies. Thus, the choice of Lean methods combined with Industry 4.0 technologies needs to be well aligned with the manufacturer's objectives, and additionally, possible trade-offs must be considered.

Keywords: Lean Management; Lean Production; Industry 4.0; Lean 4.0; Key Performance Indicator (KPI); Target Dimensions

1. Introduction

The industrial sector plays a crucial role in Europe as it is a key driver of economic growth due to its contribution to 75 % of EU's exports and 80 % of all innovations [1]. For many years, digitalization has been among the megatrends expected to shape the production's future [2]. To enhance the digitalization in industry, most of the EU's countries started national initiatives, often known as Industry 4.0 [3,4].

Industry 4.0 can be traced back to 2011 when the German government launched it as part of the German high-tech strategy [5]. Due to the increasing competition in the manufacturing industry, the need for reliable and fast solutions to increase efficiency and the demand for new business models arises. Therefore, a stepwise integration of Industry 4.0 technologies is required to react to market changes agilely. [6]

The implementation of Industry 4.0 needs to be well aligned with Lean Production, as many manufacturers have already implemented the methods and ideas of the Lean Production approach [7]. Within Lean Production, the organization and processes are treated holistically to achieve continuous improvements by eliminating all types of waste [8]. Therefore, Lean Production represents an essential starting point for integrating new technologies in the manufacturing systems [7,9]. Consequently, it is essential to analyze the role of these two paradigms within an organization and investigate their impact on target dimensions such as time, cost, or quality to create a future-proof production system [10].

Therefore, this scientific contribution provides a systematic approach to identify the implications of Lean 4.0 methods on target dimensions that are significantly important for manufacturing companies. Consequently, the paper shall

10.1016/j.procir.2022.04.034

support companies in transforming their production system and serve as an essential basis for further research.

The following section sets up the reference frame of the paper's scientific fields and introduces Lean 4.0 and the target dimension for production systems. Additionally, the current state of research is presented.

2. Fundamentals

2.1. Lean 4.0

The combination of Lean Production and Industry 4.0 is still being researched and is called Lean 4.0 [11–13]. Rittberger & Schneider [14] used the Human-Technology-Organization-Model (HTO) to compare and combine Lean Production with Industry 4.0 and to identify possible potentials [14–16].

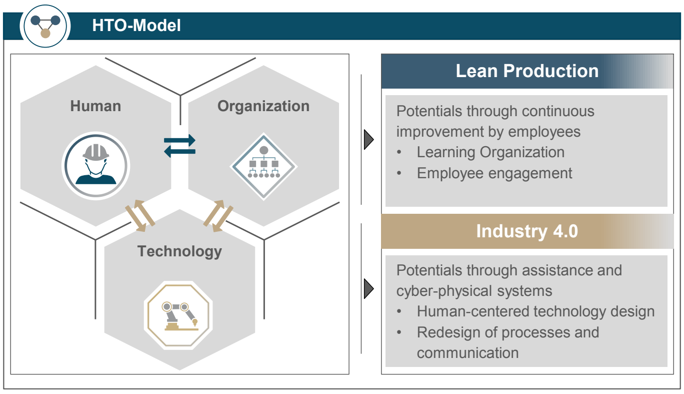

Figure 1: Human-Technology-Organization-Model for Lean Production and Industry 4.0 (according to Rittberger & Schneider [14])

Figure 1 shows that the Lean Production approach focuses on the organization and the humans, such as employees or customers, and their interaction [14]. Moreover, it is a holistic and long-term-oriented methodical approach that requires a change of employees' attitudes and awareness to reach a continuous value stream by avoiding waste [7,17]. Supplementary, Industry 4.0 is technology-focused [7,18] and requires a high degree of process orientation with clearly defined processes [17]. It covers the interface of technology with both humans and the organization [14]. Although the two paradigms take a different focus on the HTO-Model, several researchers assume positive synergies between them. The two main perspectives, as suggested by Rosin et al. [19], are "Lean Production as a basis for Industry 4.0" and "Industry 4.0 advances Lean Production".

Concerning the first perspective, many scientific papers state that Lean Production is the basis for Industry 4.0 [17,20,21], as Industry 4.0 technologies are assumed to build on the holistic approach of the Lean Production System [22]. The survey of Tortorella & Fettermann [23] confirms that Industry 4.0 is introduced more likely if Lean Production is already implemented. An essential requirement of Industry 4.0 is a certain degree of process orientation with defined processes, customers, suppliers, tasks, and times [17]. Supporting this, Lean Production Systems generate standardized, transparent, and waste-free processes [8]. Moreover, Lean Production minimizes complexity and creates higher process orientation, facilitating the implementation of Industry 4.0 technologies [11,17,24,25]. As shown in Figure 1, Lean Production is an employee-centric approach aiming to develop and encourage employees to be efficient decision-makers since they continuously consider customer value and waste avoidance [26]. These competencies are assumed to be prerequisites for a successful digital transformation in the sense of Industry 4.0 [7,13,27]. From an economic perspective, Huber [28] expects a more efficient implementation of Industry 4.0 technologies when Lean Production is already present.

The other central perspective is that technological advancements of Industry 4.0 might complete or even enhance Lean Production activities and positively affect its efficiency [17,29,30]. Bauernhansl [31] and Kieviet [27] highlight the potentials of Industry 4.0 for Lean Production Systems facing complexity and flexibility simultaneously by applying appropriate technologies. Industry 4.0 technologies are applied to gather and evaluate the process and operating data [18,32], which advances Lean Production methods, such as Total Productive Maintenance (TPM) or Jidoka, and increases a high level of self-organization [7,10]. In addition, vertical and horizontal system integration based on networking technology can improve stakeholder integration in a Lean Production System [17]. Furthermore, when introducing Industry 4.0 technologies, such as cyber-physical systems (CPS), companies can develop new business models with a higher degree of service orientation while focussing on the customer [7,10]. Also, several authors investigated the effects of Industry 4.0 technologies on continuous improvement processes within a Lean Production system and expect a positive impact of Industry 4.0 [14,33,34].

It can be stated that, according to the current state of research, there is a positive correlation between Lean Production and Industry 4.0, called Lean 4.0 [7,35]. Lean 4.0 describes the adaptability of a manufacturing company to technological and digital progress, taking into account the Lean Production philosophy. In this context, Lean 4.0 improvements need to be aligned with the company's targets and have a holistic effect and consider humans, technology, the organization, and their interactions [14,36].

2.2. Target Dimensions

Target dimensions are needed to focus on long-term, strategic company goals rather than short-term improvements [37]. According to Gottmann [38], relevant production-related targets are the magic triangle consisting of time, cost, and quality. Additionally, Liebrecht [39] extends them with the targets employee and flexibility, as these become more important due to the complex production environment [15]. The five target dimensions [39] are presented and described in the following figure (Figure 2). Due to the importance of these target dimensions, it is essential to investigate the implication of Lean 4.0 methods on the five targets.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

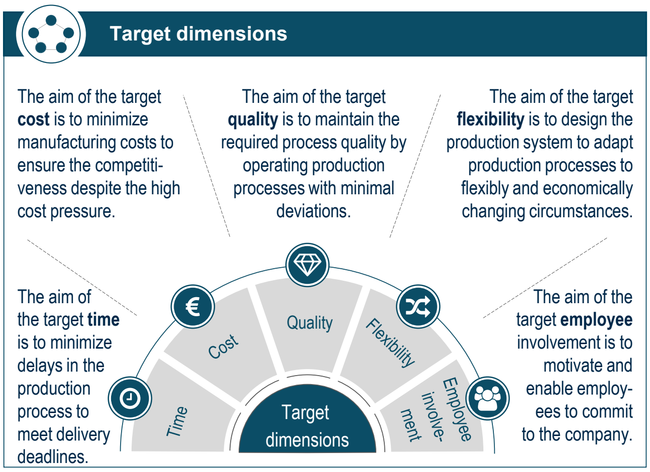

Figure 2: Target dimensions (according to Liebrecht [39])

In Lean Production, a literature analysis conducted by Sangwa & Sangwa [40] shows that the impact of Lean Production methods on relevant target dimensions is already investigated. The VDI 2870 [41] has indicated the influence of 35 Lean Production methods on the target dimensions time, costs, and quality through a four-stage Likert scale. Lean Production value stream indicators, which focus on horizontal flows and reveal the potential for improvement, have also been researched in scientific papers [12]. These performance indicators can be assigned to the different Lean Production methods along the value stream [38]. Therefore, several researchers introduced specific value stream indicators, like flow level or lead time [21,38,42].

In the context of Industry 4.0, Weyrich et al. [43], Torbacki & Kjewska [44], and Xie et al. [45] introduced several performance indicators related to Industry 4.0 without providing a way to measure those. In the framework of Industry 4.0, Joppen et al. [46] analyzed typical target dimensions, which mostly correspond to ISO 22400 [47], and investigated additional IT-related target dimensions. However, detailed descriptions are lacking as well. Additionally, Liebrecht [39] defined several scenarios for applying Industry 4.0 methods, and experts evaluated the impact on the performance dimensions. Concerning Lean 4.0, Ante et al. [12] evaluated the impact of Industry 4.0 company-specific projects, partly combined with Lean Production methods, on performance dimensions. Other researchers developed single use cases for Lean 4.0 but did not evaluate their impact on performance measurement systems [48,49].

It can be stated that there are scientific contributions that evaluate the impact of Lean Production or Industry 4.0 on relevant target dimensions. However, the researched scientific literature also indicates that the effects of Lean 4.0 methods and use cases in production on relevant target dimensions have not yet been sufficiently investigated.

3. Methodical Approach

In the following, a methodical, application-oriented approach is presented to identify the implications of Lean 4.0 methods on relevant target dimensions. Such an impact analysis should be based on a clear production perspective and include Lean 4.0 methods, use cases, and target dimensions of considerable importance for manufacturing companies. Moreover, the targeted analysis shall be based on a systemic and methodical planning procedure, as presented in Figure 3.

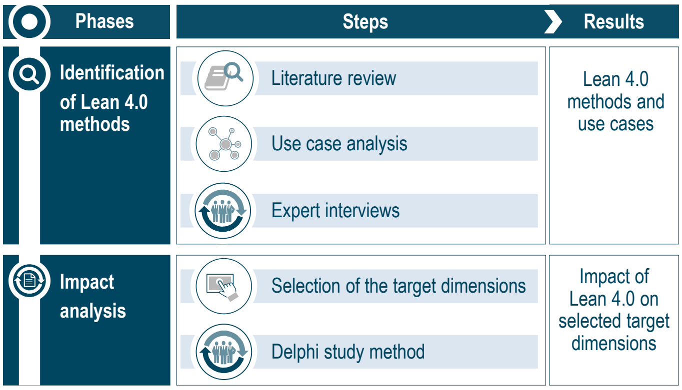

Figure 3: Procedure for the development of the impact analysis

The procedure can be divided into two main phases (Figure 3). First, the relevant Lean 4.0 methods are selected and analyzed using a structured literature analysis [37]. Based on the Lean 4.0 methods, use cases are derived, validated, and adjusted through semi-structured expert interviews. The result of the first phase is a selection of appropriate Lean 4.0 methods and use cases.

The Lean 4.0 methods' impact on target dimensions needs to be investigated in the second phase. Therefore, expert interviews are conducted according to the Delphi study method and combined with a Likert scale. The Delphi study method is a feedback technique with a panel of five to twenty experts [50]. The feedback will be given anonymously to counteract group dynamics [51]. The following chapter describes the selection of the Lean 4.0 methods and presents the impact analysis.

4. Implications of Lean 4.0 Methods on Relevant Target Dimensions

4.1. Phase 1: Identification of Lean 4.0 Methods

First, a literature review was conducted to identify relevant Lean 4.0 methods. The review was based on the database Scopus and referred to appropriate contributions from Lean 4.0, with search terms leading on Industry 4.0 technology fields according to Ruessmann et al. [52] and selected Lean Production methods [53]. Also, a publication period between 2011 and 2021 and the restriction to conference papers, reviews, and articles from the research area engineering was chosen as limits.

The selected scientific contributions were used to derive use cases, characterized according to five main components [54]: Definition of the scope, actors, the level of the use cases, Lean Production methods, and Industry 4.0 technologies. The use cases' scope comprises production and production-related areas such as logistics and maintenance. The Lean 4.0 methods trigger an interaction with the production system and people such as shopfloor, logistics, or maintenance employees. Depending on the Lean 4.0 method, the observation level ranges from the enterprise, factory, shopfloor, cell, and machine [55]. The identified fourteen Lean 4.0 use cases with selected

Lean Production methods, and Industry 4.0 technologies are categorized below based on expert interviews and the identified literature (Figure 4).

Lean 4.0 methods

Legend:
- ● characteristic is fulfilled
- 0 characteristic is partially fulfilled
- □ characteristic is not fulfilled

	JiT with CPS [13,48,56–59]	JiT with AGVs [13,31,60,61]	TPM 4.0 [13,62]	TPM with analytics [7,56,61,63]	eKanban with IIoT [7,13,56,64]	Kanban with Simulation [11,13,61]	VSM with CPS [13,61,65,66]	VSM with simulation [61,67]	SMED with p&p [11,20,56,68]	SMED with additive manufacturing [69]	Jidoka with intelligent objects [7,20,70]	Jidoka with sensors and actuators [7,71]	Heijunka with H&V [48,72,73]	Heijunka with data analytics [13,27,48]
Scope														
Production	0	0			0	0	●	●	●	●	●	●	●	●
Logistics	●	●			●	●	●	●					0	0
Maintenance			●	●							0	0		
Actor (employee)														
Shopfloor employee	0	0			0	0	●	●	●	●	●	●	●	●
Logistics employee	●	●			●	●	●	●					0	0
Maintenance employee			●	●							0	0		
Level														
Enterprise-level	0	0			0	0	●	●					●	0
Factory-level	●	●	0	0	●	●	●	●			0	0	●	●
Shopfloor-level	●	●	0	0	●	●	●	●	0	0	●	●	●	●
Cell-level	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Machine-level	0		●	●			0	0	●	●	●	●	●	●
Lean Production														
Heijunka													●	●
Jidoka											●	●		
Just-in-Time (JiT)	●	●												
Kanban					●	●								
Single Minute Exchange of Die (SMED)									●	●				
Total Productive Maintenance (TPM)			●	●										
Value stream mapping (VSM)							●	●						
Industry 4.0														
Additive manufacturing										●				
Augmented reality			●								●			
Auto-ID	●	●			●		●		●			●	●	●
Autonomous guided vehicle (AGV)		●												
Big data and analytics	●		●	●	●		●		●		●			●
CAD-Model						●		●						
Cloud technology	●		●								●			
Cyber-physical system (CPS)	●										●	●		
Digital twin						●		●						
Horizontal & vertical integration (H&V)													●	
Intelligent objects	●			●							●	●		
Industrial internet of things (IIoT)	●										●		●	
Machine-to-machine communication									●	●			●	
Plug and produce (p&p)									●					
Real-time data	●	●	●	●			●				●	●	●	●
Sensors and actuators		●	●	●			●		●		●	●	●	●
Simulation						●								●
Virtual Reality			●											

Figure 4: Procedure for the development of the impact analysis

Based on the Lean 4.0 methods' categorization (Figure 4), descriptions were created and validated for each use case. This ensures a common understanding of the use cases among the experts surveyed in phase 2.

4.2. Phase 2: Analysis of the Implications

First, the relevant target dimensions need to be identified. The selection of the target dimensions is based on the scientific contribution of Liebrecht [39], who identified cost, quality, time, employee, and flexibility as particularly relevant for companies (Figure 2).

Afterward, based on the use cases, nine experts from science and research were interviewed to figure out the impact of Lean 4.0 methods on the target dimensions using a seven-point Likert scale (Figure 5). The feedback was given anonymously to counteract group dynamics. For Delphi studies, the sampling of the experts is essential [51,74]. Therefore, the panel consists of five experts from science and four from industry to consider both perspectives. First, the experts assessed the impact independently. Afterward, the questionnaires were collected, the mean values were calculated, and the experts received the summarized results to validate and, if necessary, modify them. The final result of the impact analysis of the Lean 4.0 methods on the target dimensions is shown in Figure 5.

Impact of Lean 4.0 methods on target dimensions

Legend | Likert scale:

Impact	Description
-3	Strong negative
-2	Medium negative
-1	Low negative
0	No impact
1	Low positive
2	Medium positive
3	Strong positive

	JiT with CPS	JiT with AGVs	TPM 4.0	TPM with analytics	eKanban with IIoT	Kanban with Simulation	VSM with CPS	VSM with simulation	SMED with p&p	SMED with additive manufacturing	Jidoka with intelligent objects	Jidoka with sensors and actuators	Heijunka with H&V	Heijunka with data analytics	**Overall average**
Time	2.0	1.9	1.8	2.0	2.4	2.3	2.6	2.6	2.8	1.9	2.2	1.8	2.3	2.1	**2.2**
Cost	1.1	1.0	1.8	2.1	1.9	2.4	1.8	2.4	1.8	0.9	2.2	2.0	1.7	1.6	**1.8**
Quality	1.8	1.7	1.9	2.2	1.4	1.8	1.2	1.7	1.4	0.6	2.9	2.8	1.3	1.2	**1.7**
Employee involvement	0.8	-0.7	2.0	1.4	0.8	0.8	0.4	0.7	1.8	0.9	1.0	0.1	0.8	0.7	**0.8**
Flexibility	1.3	1.3	1.7	1.7	1.7	1.7	1.6	1.6	2.7	2.8	1.7	0.6	2.0	1.4	**1.7**
Overall average	**1.4**	**1.0**	**1.8**	**1.9**	**1.6**	**1.8**	**1.5**	**1.8**	**2.1**	**1.4**	**2.0**	**1.5**	**1.6**	**1.4**	**1.6**

Figure 5: Impact of Lean 4.0 methods on target dimensions

5. Results and Discussion

In the following section, the impact analysis results are interpreted. A total of 70 impact relationships between Lean 4.0 methods and the target dimensions were analyzed, of which seven (10 %) had a high positive impact, 38 (54.3 %) a medium positive impact, 22 (31.4 %) a low positive impact, two (2.9 %) no impact and one (1.4 %) a low negative impact. Ten of the fourteen Lean 4.0 methods had a medium positive overall average impact on the target dimensions (between 1.5 and 2.4). Only four Lean 4.0 methods had, on average, a low positive impact on the five target variables (between 0.5 and 1.4). In addition, the selected Lean 4.0 methods had, on average, a medium positive impact on the dimensions of time (2.2), costs (1.8), quality (1.7), and flexibility (1.7). For the dimension employee involvement, the average value is 0.8, which means a low positive impact. This may result from the selection of the Lean 4.0 methods (Figure 4), as employee-oriented Lean Production methods, such as multi-machine operation or multidisciplinary trained employees [75] in combination with Industry 4.0 technologies, were not considered.

Overall, it can be stated that 95.7 % of the impact relationships have at least a low positive impact. Only the impact of the Lean 4.0 method "JiT with AGVs" has a negative impact (-0.7) on the target dimension employee involvement. An autonomous guided vehicle may replace a logistics employee. However, the employee could pursue other activities and, for example, work as a point-of-use provider to support the workers on the shop floor level. Thus the process stability in the sense of the Lean Production method Just-in-Time delivery would increase. The implications of the Lean 4.0 methods "VSM with CPS" (2.6), "VSM with simulation" (2.6), and "SMED with plug and produce" (2.8) on the target time were rated particularly positively. With regard to VSM, this can be attributed to the fact that the key process parameters, such as lead times or inventories, can be transmitted and monitored in real-time and in accordance with the actual state. If there are deviations from the target state, it is possible to react immediately if necessary and to initiate improvements, which leads, for example, to a reduction in lead times and idle production time.The Lean 4.0 methods "Jidoka with intelligent objects" (2.9) and "Jidoka with sensors and actuators" (2.8) have the highest positive impact on the quality target. The Industry 4.0 technologies support the Lean Production method Jidoka in preventing errors through intelligent objects, sensors, or actuators. On the other hand, the Lean 4.0 methods "SMED with plug and produce" (2.7) and "SMED with additive manufacturing" (2.8) have a very positive impact on the target parameter flexibility. Both SMED and the two Industry 4.0 technologies are characterized by the fact that they reduce setup times, or in the case of Industry 4.0 technologies, almost eliminate them, which is the reason for the very positive impact on flexibility.

In summary, it can be stated that the fourteen Lean 4.0 methods predominantly have a positive impact on the selected target dimensions. This is particularly the case on time, costs, quality, and flexibility dimensions. Moreover, none of the 14 Lean 4.0 methods has a very high positive impact (> 2.5) on all five target dimensions. In order to achieve the manufacturing companies' targets, it is essential to systematically introduce the Lean 4.0 methods and follow an implementation strategy since the single methods have an impact on different target dimensions.

6. Conclusion and Outlook

This research contribution presents a comprehensive and structured impact analysis to identify Lean 4.0 methods and analyze their impact on the target dimensions: cost, quality, time, employee involvement, and flexibility. The Lean 4.0 methods were identified by a comprehensive literature analysis and afterward characterized to derive Lean 4.0 use cases for each method. Based on the validated use cases, the impact analysis of Lean 4.0 on relevant target dimensions was conducted by using a Delphi study method. It can be stated that the majority of the Lean 4.0 methods have a positive influence on the target dimensions, but non has a high positive impact on all five dimensions. Therefore, it is essential to systematically introduce the Lean 4.0 methods by following an implementation strategy.

Building on these findings and the presented procedure, the impact of Lean 4.0 on additional target dimensions, like, e.g., sustainability, needs to be explored. Future studies with additional panelists could also investigate the influence on more detailed Key Performance Indicators like overall equipment effectiveness or first-pass yield, or could include Lean 4.0 methods, like Hoshin Kanri 4.0 or Kaizen 4.0.

References

[1] Dujin A, Geissler C, Horstkötter D. *Industry 4.0 The new industrial revolution – How Europe will succeed*. http://www.iberglobal.com/files/Roland_Berger_Industry.pdf (accessed on 02.12.2021).

[2] Abele E, Metternich J, Tisch M (2019) *Learning Factories: Concepts, guidelines, best-practice examples*. Springer International Publishing, Cham.

[3] Federal Ministry for Economic Affairs and Energy. *Plattform Industrie 4.0*. https://www.plattform-i40.de/PI40/Navigation/Karte/SiteGlobals/Forms/Formulare/EN/map-use-cases-formular.html (accessed on 28.11.2021).

[4] European Commission. *European Commission: Coordination of European, national & regional initiatives. Shaping Europe's digital future*. https://ec.europa.eu/digital-single-market/en/coordination-european-national-regional-initiatives (accessed on 02.12.2021).

[5] Kagermann H, Wahlster W, Helbig J (2013) *Umsetzungsempfehlungen für das Zukunftsprojekt Industry 4.0: Abschlussbericht des Arbeitskreises Industry 4.0*.

[6] VDI/VDE 4000 Blatt 1 (2021) *Systematische Transformation und Evaluation von Produktionssystemen - Grundlagen*.

[7] Metternich J, Müller M, Meudt T, Schaede C (2017) Lean 4.0 – zwischen Widerspruch und Vision. *ZWF* 112(5):346–8.

[8] Ōno T (2013) *Das Toyota-Produktionssystem: Das Standardwerk zur Lean Production.* 3rd ed. Campus-Verl., Frankfurt am Main.

[9] Dillinger F, Formann F, Reinhart G (2020) Lean Production und Industrie 4.0 in der Produktion: Eine Studie zur Wechselwirkung und den gemeinsamen Potenzialen. *ZWF* 115(10):738–41.

[10] Bick W (2014) Produktionsmanagement. Warum Industrie 4.0 und Lean zwingend zusammengehören. *Produktionsmanagement* 156(11):46–7.

[11] Dennis K, Detlef Zühlke (2015) Lean Automation enabled by Industry 4.0 Technologies. *IFAC-PapersOnLine*:1870–5.

[12] Ante G, Facchini F, Mossa G, Digiesi S (2018) Developing a key performance indicators tree for lean and smart production systems. *IFAC-PapersOnLine* 51(11):13–8.

[13] Mayr A, Weigelt M, Kühl A, Grimm S, Erll A, Potzel M, Franke J (2018) Lean 4.0 - A conceptual conjunction of lean management and Industry 4.0. *Procedia CIRP* 72:622–8.

[14] Rittberger S, Schneider M (2018) Continuous Improvement of Lean Processes with Industry 4.0 technologies. *11th International Doctoral Students Workshop on Logistics*.

[15] Reinhart G, (Ed.) (2017) *Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik*. Hanser, München.

[16] Tropschuh B, Dillinger F, Korder S, Maier M, Gärtner Q, Vernim S (2021) Industrie 5.0 – ein menschzentrierter Ansatz. *ZWF* 116(6):387–92.

[17] Dombrowski U, Richter T, Krenkel P (2017) Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis. *Procedia Manufacturing* 11:1061–8.

[18] Dillinger F, Messmer C, Reinhart G (2021) Industrie-4.0-Technologiekreis für produzierende Unternehmen. *ZWF* 116(9):639–43.

[19] Rosin F, Forget P, Lamouri S, Pellerin R (2020) Impacts of Industry 4.0 technologies on Lean principles. International Journal of Production Research, 1-18. *International Journal of Production Research* 58(6):1644–61.

[20] Mrugalska B, Wyrwicka MK (2017) Towards Lean Production in Industry 4.0. *Procedia Engineering* 182:466–73.

[21] Bertagnolli F (2018) *Lean Management: Einführung und Vertiefung in die japanische Management-Philosophie*. Springer Gabler, Wiesbaden, Heidelberg.

[22] Bauernhansl T, Hompel M ten, Vogel-Heuser B (2014) *Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration*. Springer Fachmedien Wiesbaden, Wiesbaden.

[23] Tortorella GL, Fettermann D (2018) Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International Journal of Production Research* 56(8):2975–87.

[24] Hermann M, Pentek T, Otto B (2016) Design Principles for Industrie 4.0 Scenarios:3928–37.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

[25] Soder J (2014) Use Case Production: Von CIM über Lean Production zu Industrie 4.0. in Bauernhansl T, Hompel M ten, Vogel-Heuser B, (Eds.). *Industrie 4.0 in Produktion, Automatisierung und Logistik*. Springer Fachmedien Wiesbaden. Wiesbaden, pp. 85–102.
[26] Liker JK (2013) *Toyota way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill Education; McGraw Hill, New York, N.Y.
[27] Kieviet A (2016) Digitalisierung der Wertschöpfung: Auswirkung auf das Lean Management. in Künzel H, (Ed.). *Erfolgsfaktor Lean Management 2.0*. Springer Berlin Heidelberg. Berlin, Heidelberg, pp. 41–59.
[28] Huber W (2016) *Industrie 4.0 in der Automobilproduktion: Ein Praxisbuch*. Springer Fachmedien Wiesbaden, Wiesbaden.
[29] Prinz C, Kreggenfeld N, Kuhlenkötter B (2018) Lean meets Industrie 4.0 – a practical approach to interlink the method world and cyber-physical world. *Procedia Manufacturing* 23:21–6.
[30] Rüttimann BG, Stöckli MT (2016) Lean and Industry 4.0—Twins, Partners, or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems. *JSSM* 09(06):485–500.
[31] Bauernhansl T (2014) *Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung · Technologien · Migration*. Springer, Dordrecht.
[32] Wang S, Wan J, Di Li, Zhang C (2016) Implementing Smart Factory of Industrie 4.0: An Outlook. *International Journal of Distributed Sensor Networks* 12(1):3159805.
[33] Hambach J, Kümmel K, Metternich J (2017) Development of a Digital Continuous Improvement System for Production. *Procedia CIRP* 63:330–5.
[34] Meudt T, Metternich J, Abele E (2017) Value stream mapping 4.0: Holistic examination of value stream and information logistics in production. *CIRP Annals* 66(1):413–6.
[35] Dillinger F, Kagerer M, Reinhart G (2021) Concept for the development of a Lean 4.0 reference implementation strategy for manufacturing companies. *Procedia CIRP* 104:330–5.
[36] Dombrowski U, Krenkel P, Falkner A, Placzek F, Hoffmann T (2018) Prozessorientierte Potenzialanalyse von Industrie 4.0-Technologien: Zielorientiertes Auswahlverfahren. *ZWF* 113(3):107–11.
[37] Gladen W (2014) *Performance Measurement*. Springer Fachmedien Wiesbaden, Wiesbaden.
[38] Gottmann J (2019) *Produktionscontrolling: Wertströme und Kosten optimieren.* 2nd ed. Springer Gabler, Wiesbaden, Heidelberg.
[39] Liebrecht C (2020) Entscheidungsunterstützung für den Industrie 4.0-Methodeneinsatz: Strukturierung, Bewertung und Ableitung von Implementierungsreihenfolgen, Dissertation, Aachen.
[40] Sangwa NR, Sangwan KS (2018) Development of an integrated performance measurement framework for lean organizations. *JMTM* 29(1):41–84.
[41] VDI 2870-1 (2012) *Ganzheitliche Produktionssysteme. Grundlage, Einführung und Bewertung*.
[42] Rother M, Shook J (2003) *Learning to see: Value-stream mapping to create value and eliminate muda.* 1st ed. Lean Enterprise Inst, Cambridge, Mass.
[43] Weyrich M, Klein M, Schmidt J-P, Jazdi N, Bettenhausen KD, Buschmann F, Rubner C, Pirker M, Wurm K (2017) Evaluation Model for Assessment of Cyber-Physical Production Systems. in Jeschke S, Brecher C, Song H, Rawat DB, (Eds.). *Industrial Internet of Things*. Springer International Publishing. Cham, pp. 169–199.
[44] Torbacki W, Kijewska K (2019) Identifying Key Performance Indicators to be used in Logistics 4.0 and Industry 4.0 for the needs of sustainable municipal logistics by means of the DEMATEL method. *Transportation Research Procedia* 39:534–43.
[45] Xie Y, Yin Y, Xue W, Shi H, Chong D (2020) Intelligent supply chain performance measurement in Industry 4.0. *Syst Res Behav Sci* 37(4):711–8.
[46] Joppen R, Enzberg S von, Gundlach J, Kühn A, Dumitrescu R (2019) Key performance indicators in the production of the future. *Procedia CIRP* 81:759–64.
[47] International Organization for Standardization 22400 (2024) *Automation systems and integration — Key performance indicators (KPIs) for manufacturing operations management*(Part 2). Beuth Verlag GmbH, Berlin.
[48] Wagner T, Herrmann C, Thiede S (2017) Industry 4.0 Impacts on Lean Production Systems. *Procedia CIRP* 63:125–31.
[49] Shahin M, Chen FF, Bouzary H, Krishnaiyer K (2020) Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises. *Int J Adv Manuf Technol* 107(5-6):2927–36.
[50] Grime MM, Wright G (2014) D elphi Method. in Balakrishnan N, Colton T, Everitt B, Piegorsch W, Ruggeri F, Teugels JL, (Eds.). *Wiley StatsRef: Statistics Reference Online*. John Wiley & Sons, Ltd. Chichester, UK, pp. 1–6.
[51] Schmidt RC (1997) Managing Delphi Surveys Using Nonparametric Statistical Techniques. *Decision Sciences* 28(3):763–74.
[52] Rüßmann M, Lorenz M, Gerbert P, Waldner M, Justus J, Engel P, Harnisch M (2015) Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. *Germany - DE,* 9 April 2015. https://www.bcg.com/de-de/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.
[53] Aull F (2013) *Modell zur Ableitung effizienter Implementierungsstrategien für Lean-Production-Methoden*. Zugl.: München, Techn. Univ., Diss., 2012. Utz, München.
[54] Cockburn A (2008) *Use cases effektiv erstellen.* 1st ed. mitp, Heidelberg.
[55] Stich V, Blum M (2015) A Cybernetic Reference Model for Production Systems Using the Viable System Model. in Umeda S, Nakano M, Mizuyama H, Hibino N, Kiritsis D, Cieminski G von, (Eds.). *Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth*. Springer International Publishing. Cham, pp. 169–176.
[56] Sanders A, Elangeswaran C, Wulfsberg J (2016) Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *JIEM* 9(3):811.
[57] Srinivasan S, Ganesh Prasad P (2017) The role of Intelligent Automation, Big Data and Internet of Things in Manufacturing - A Survey. *Imperial Journal of Interdisciplinary Research (IJIR)*(3):934–40.
[58] Fescioglu-Unver N, Choi SH, Sheen D, Kumara S (2015) RFID in production and service systems: Technology, applications and issues. *Inf Syst Front* 17(6):1369–80.
[59] Ding K, Jiang P (2018) RFID-based production data analysis in an IoT-enabled smart job-shop. *IEEE/CAA J. Autom. Sinica* 5(1):128–38.
[60] Kaspar S, Schneider M (2015) Lean und Industrie 4.0 in der Intralogistik: Effizienzsteigerung durch Kombination der beiden Ansätze. *productivity* 20(5):17–20.
[61] Valamede LS, Akkari ACS (2020) Lean 4.0: A New Holistic Approach for the Integration of Lean Manufacturing Tools and Digital Technologies. *Int J Math, Eng, Manag Sci* 5(5):851–68.
[62] Palmarini R, Erkoyuncu JA, Roy R, Torabmostaedi H (2018) A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing* 49:215–28.
[63] Jardine AK, Lin D, Banjevic D (2006) A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing* 20(7):1483–510.
[64] Dickmann P (2015) *Schlanker Materialfluss: Mit Lean Production, Kanban und Innovationen.* 3rd ed. Springer Vieweg, Berlin, Heidelberg.
[65] Ramadan M, Salah B (2019) Smart Lean Manufacturing in the Context of Industry 4.0: A Case Study. *International Journal of Industrial and Manufacturing Engineering* 13(3):174–81.
[66] Huang Z, Kim J, Sadri A, Dowey S, Dargusch MS (2019) Industry 4.0: Development of a multi-agent system for dynamic value stream mapping in SMEs. *Journal of Manufacturing Systems* 52:1–12.
[67] Esfandyari A, Osman MR, Ismail N, Tahriri F (2011) Application of value stream mapping using simulation to decrease production lead time: a Malaysian manufacturing case. *IJISE* 8(2):230.
[68] Brettel M, Friederichsen N, Keller M, Rosenberg M (2014) How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* 8(1):37–44.
[69] Feldmann C, Gorj A (2017) *3D-Druck und Lean Production: Schlanke Produktionssysteme mit additiver Fertigung*. Springer Gabler, Wiesbaden.
[70] Kolberg D, Zühlke D (2015) Lean Automation enabled by Industry 4.0 Technologies. *IFAC-PapersOnLine* 48(3):1870–5.
[71] Ma J, Wang Q, Zhao Z (2017) SLAE-CPS: Smart Lean Automation Engine Enabled by Cyber-Physical Systems Technologies. *Sensors (Basel, Switzerland)* 17(7).
[72] Siepmann D, Graef N (2016) Industrie 4.0 – Grundlagen und Gesamtzusammenhang. in Roth A, (Ed.). *Einführung und Umsetzung von Industrie 4.0*. Springer Berlin Heidelberg. Berlin, Heidelberg, pp. 17–82.
[73] Kaufmann T, Forstner L (2017) Die horizontale Integration der Wertschöpfungskette in der Halbleiterindustrie – Chancen und Herausforderungen. in Vogel-Heuser B, Bauernhansl T, Hompel M ten, (Eds.). *Handbuch Industrie 4.0 Bd.4*. Springer Berlin Heidelberg. Berlin, Heidelberg, pp. 127–135.
[74] Nakatsu RT, Iacovou CL (2009) A comparative study of important risk factors involved in offshore and domestic outsourcing of software development projects: A two-panel Delphi study. *Information & Management* 46(1):57–68.
[75] Dillinger F, Martl N, Reinhart G (2021) Lean-Production-Methoden und Industrie-4.0-Technologien in der Produktion: Eine Studie zur

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.

Einführungsdauer und Relevanz. *ZWF* 116(12).