The International Journal of Advanced Manufacturing Technology (2020) 107:2927–2936
https://doi.org/10.1007/s00170-020-05124-0

ORIGINAL ARTICLE

Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises

Mohammad Shahin[1] · F. Frank Chen[1] · Hamed Bouzary[1] · Krishnan Krishnaiyer[1]

Published online: 28 March 2020
© Springer-Verlag London Ltd., part of Springer Nature 2020

Abstract
Industry 4.0 technologies have attempted to transform current industrial settings to a level that we have never seen before. While at the same time, prevailing applications of Lean tools and techniques over the last 20 years have already dramatically reduced wastes ranging from shop floor production to cross-functional enterprise processes. This paper aims to provide a comprehensive review and report on links between Lean tools and Industry 4.0 technologies, and on how simultaneous implementation of these two paradigms affects the operational performance of factories. The existing and potential enhancements of Lean practices enabled by Industry 4.0 technologies such as wireless networks, big data, cloud computing, and virtual reality (VR) will also be explored. A cloud-based Kanban decision support system is also presented as a real-world demonstrator for integration of an Industry 4.0 technology (cloud computing) and a major Lean tool (Kanban).

Keywords Industry 4.0 · Lean tools · Smart factory · Cloud Kanban

1 Introduction

Implementation of Lean manufacturing concept has given rise to significant positive impacts on various industries during the past couple of decades. The concept of Lean production was first introduced by Womack et al. [1] inspired by the Toyota Production Systems (TPS). TPS provided tools and methodologies to eliminate waste in an effective, but mostly problem-specific way. Hence, Womack and Jones [2] systematized the *Lean Thinking* and put together five critical elements of Lean implementation, i.e., value, value stream, continuous flow, pull, and the continuous improvement. Although Lean tools and techniques have already proven their efficacy in various sectors, it seems as if Lean production, on its own, is not capable of coping with the current market dynamics anymore [3]. Strong market demand fluctuations do not go in line with the capacity leveling concept. In addition, the lack of changeability in production lines and the fact that laborious adjustments are required for changes in production processes, buffer stocks and cycle times, are all indicating that Lean tools and techniques are of limited suitability when it comes to shorter product life cycles and highly customized products [3, 4].

To keep up with the aforementioned high demand for customized products, tighter competition and increased emphasis on immediate and responsive service, companies are being directed towards digital transformation and service-oriented paradigms. This transformation has been accelerated recently thanks to the increasingly affordable hardware and software solutions realized by cheaper and more effective sensors and actuators, more powerful networking equipment and platforms such as wireless technology and cloud computing and also Big data analytics and artificial intelligence related developments. These components form the recently introduced "Industry 4.0" concept targeting the digitization and automatization of production. However, the thirst for adoption of I4.0 technologies can pose ever greater challenges in terms of cost-benefit justification, implementation considerations and frameworks, and its influence on already established production practices such as Lean manufacturing [5, 6].

This paper aims for covering this new area through first exploring the research work done to date regarding the link between Lean implementation and I4.0 technologies. Then we will go further with introducing a cloud Kanban framework with its underlying architecture and interfaces as a real-case demonstrator of integration of a Lean tool and an Industry 4.0 technology. The remainder of this paper is organized as

✉ F. Frank Chen
ff.chen@utsa.edu

1 Department of Mechanical Engineering, The University of Texas at San Antonio, one UTSA circle, TX78249, San Antonio, USA

follows. "Industry 4.0" section offers a clear definition of Industry 4.0 and a classification regarding its technologies, processes and characteristics. In the "Correlation between Industry 4.0 and Lean manufacturing," section, correlation between Industry 4.0 technologies and Lean tools are discussed. In the "Use case: a cloud Kanban," section, we provide our newly developed cloud-based Kanban framework as a real-world demonstrator regarding integration of an Industry 4.0 technology (cloud computing) and a major Lean tool (Kanban). The "Summary and conclusion" section provides conclusions of this paper.

2 Industry 4.0

The idea of interconnectedness of "all things" has made such a progress in recent years that made the vision of a fourth industrial revolution seem within reach like never before [5, 7]. The concept of "Industry 4.0," since its announcement at the Hannover Messe in 2011, has been discussed intensively in both industry and academia. There is, however, still a considerable amount of ambiguity regarding this term, and some overlapping, but distinct concepts and terminologies such as "IoT," "cyber-physical systems (CPS)" [8, 9], etc. have been misused for it. As a result, it is of paramount importance to demystify these terms and delineate clearly between them to bring a mutual understanding of Industry 4.0 among researchers and practitioners. In general, Industry 4.0 represents the current trend of automation technologies in the manufacturing industry, and it mainly includes enabling systems such as the cyber-physical systems (CPS), Internet of Things (IoT), and semantic machine-to-machine [10–12]. According to Germany Trade & Invest (GTAI) [13], Industry 4.0 represents the technological evolution from embedded systems to cyber-physical systems [14]. In Industry 4.0, various technologies such as RFID [15], cloud computing [16, 17], augmented reality/virtual reality (AR/VR), sensors/actuators [18, 19], and big data [20–22] are contributing to realize these underlying systems in order to integrate virtual space with the physical world. On the other hand, IoT can be defined as "*a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual* '*Things*' *have identities*, *physical attributes*, *and virtual personalities and use intelligent interfaces*, *and are seamlessly integrated into the information network*" [23]. Xu et al. [14] clearly discuss the technologies and devices that are used to support IoT (please refer to Figs. 2 and 4 in [14] for a clear representation of IoT building technologies and devices, and the correlation between IoT and CPS, respectively).

Although researchers have different opinions regarding which elements compose Industry 4.0 and how these components relate to each other, a rather clear structure of Industry 4.0 along with its associated technologies, systems, and characteristics has been proposed by Dombrowski et al. [24] based on 260 use cases of applied Industry 4.0 technologies in the German industry. A modified variation of this structure is shown in Fig. 1. As one can see from this figure, big data, RFID and identification technologies (including QR codes and NFC (near field communication) tags), cloud computing, augmented reality and virtual reality, sensors and actuators (including WSN (wireless sensor networks [25]), real-time data, automated guided vehicles, and mobile electronics (such as mobile phones, tablets)) are categorized as the technologies of Industry 4.0. In addition, smart data, internet of things, cyber-physical systems, semantic machine-to-machine communication, and digital twin can be realized only by using these technologies and can be assigned to the category of Industry 4.0 systems. If these technologies and systems of Industry 4.0 have been implemented, they can have a direct effect on the process itself and as a result, the process-related level of Industry 4.0 elements such as horizontal and vertical integration and real-time data/analytics could be achieved. Considering the rapid pace of technological developments in this field, this kind of categorizations are obviously subject to change and must be updated and extended accordingly as new technologies emerge and existing ones mature.

3 Correlation between Industry 4.0 and Lean manufacturing

3.1 Effects

Lean manufacturing has been around for quite some time and it has proven its effectiveness over these years [26, 27]. It can be defined as "*an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier*, *customer*, *and internal variability*" [28]. In fact, it seeks waste reduction through a bundle of organizational practices, instead of emphasizing on new technology implementations or resource planning. On the other hand, research works such as the one done by Moeuf et al. [29] has already reported performance benefits of implementing Industry 4.0 technologies, ranging from increased flexibility to improved productivity, reduced cost, reduced delivery time, and improved quality. However, with all these in mind, the important question that arises here is how a simultaneous implementation of both Lean concepts and Industry 4.0 technologies affect the operational performance of various enterprises. This section addresses this pivotal issue through reviewing and summarizing the research work done to date revolving this question. Table 3 provides a summary of these papers.

Wagner et al. [36] developed an impact matrix in order to achieve a decision supporting framework to identify potential

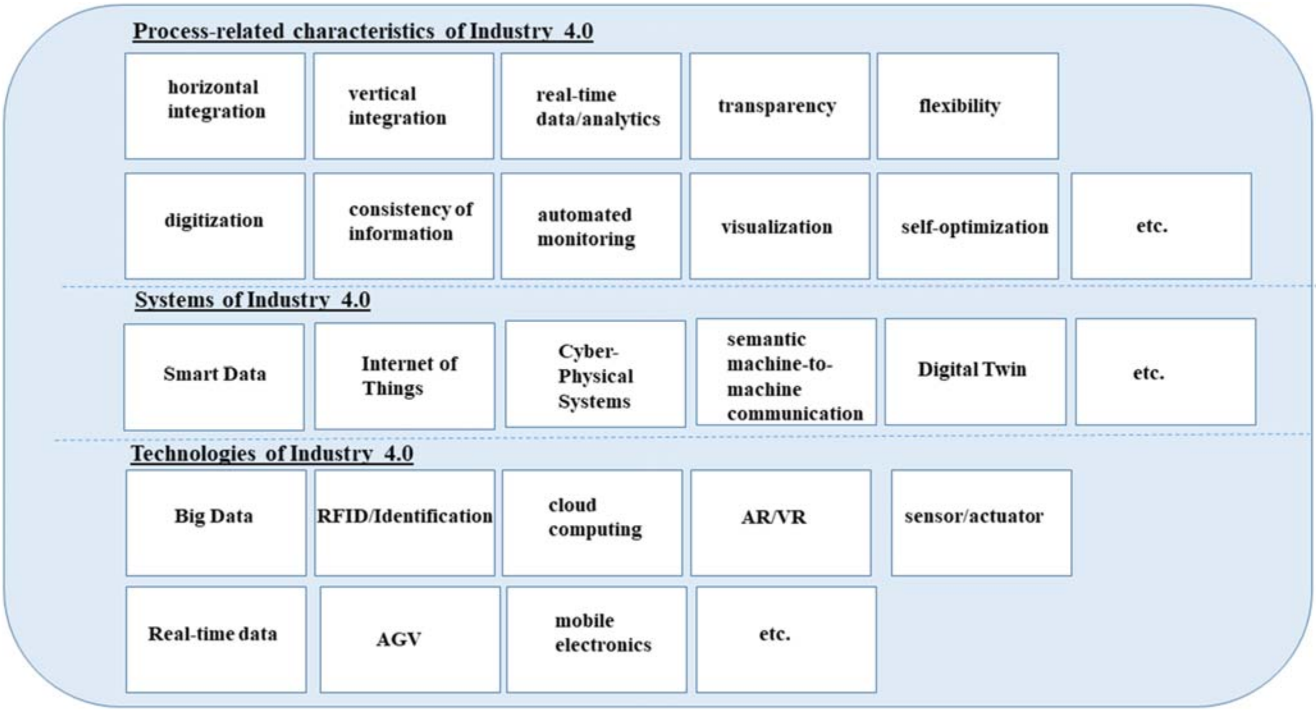


Fig. 1 Industry 4.0 technologies, systems, and process-related characteristics (inspired from [24])

Industry 4.0 solutions in the environment of a Lean production system. The matrix reflects the results of a questionnaire from a set of 24 Industry 4.0 project leaders from automotive industry. In addition, they have developed a cyber-physical Just-in-Time delivery solution and then assessed it based on the presented impact matrix.

Satoglu et al. [31] argued that implementing Industry 4.0 technologies solely cannot address the issues rooted in mismanagement or disorganization. In fact, these technologies should be applied to Lean activities that are performed successfully before automatization. They also emphasize on the importance of an effective information flow both before and after implementing these technologies.

Tortorella et al. [30] investigated the moderating effect of Industry 4.0 on the relationship between Lean concepts (specifically Pull practices, continuous flow practices and, low setup time) and operational performance. They carried out a couple of hypothesis tests on the data obtained from 147 Brazilian manufacturing companies that have implemented both Industry 4.0 technologies and Lean tools. According to their results, technologies related to products or services appear to positively moderate the relationship between continuous flow and operational performance improvement, while process-related technologies seem to moderate the effect of low setup time negatively (which is not in line with the common belief, suggesting that Industry 4.0 technologies that are primarily focused on manufacturing processes positively reinforce the relationship between Lean management practices and operational performance indicators [37]). These findings suggest that the effects associated with Lean implementation might change when Industry 4.0 practices are implemented simultaneously. This research provides a useful guidance for managers and practitioners regarding the right balance between the adoption of Industry 4.0 technologies and Lean tools and techniques.

Khanchanapong et al. [32] conducted an empirical study using data collected from 186 manufacturing plants in Thailand, investigating the unique and complementary effects of advanced manufacturing technologies (including robots, real-time process-control systems, and computer-aided manufacturing) and Lean practices on operational performance. The results obtained from the hypothesis tests conducted proved that a significant positive interaction effect exists between them on cost, product quality, lead-time, and flexibility. Based on these findings, the authors suggest that firms should invest in both of these paradigms simultaneously, rather than choosing one over the other.

Riezebos et al. [33] reviewed the effect of IT in achieving the principles of Lean production through a topical and historical approach. They have concluded that the origins of different approaches were similar, but that subsequent developments followed in opposite directions. They also reported that, later on, when the acceptance of Lean manufacturing became more pervasive, the practices typically converged into hybrid production systems, applying elements of several systems in a way that was consistent with the principles of Lean manufacturing. However, it has to be noticed that this research has only considered the centralized IT systems, leaving out the more recent distributed structures resulting from cloud technologies [38]. These cloud-based structures are more in line with the Lean philosophy in which team working is emphasized and responsibility and authority are delegated to the workforce. As a result, most of the contradictions between IT systems and Lean principles mentioned in this article will be no longer relevant.

Azadeghan et al. [35] found out that "environmental complexity" positively moderates the effects of Lean practices on operational performance through conducting regression analysis on the data obtained from 126 publicly traded manufacturers in the USA. Although this may not sound directly relevant to our topic, considering the definition of "environmental complexity" as "*a quantified indicator representing the multiplicity of inputs and outputs in the production process*," we could argue that a separate study regarding the effect of implementation of Industry 4.0 techniques on the "environmental complexity" could help us deduce if a specific Industry 4.0 technology could help by moderating the effect of Lean techniques on the production performance.

Dombrowski et al. [24] quantitatively evaluated the interdependencies between Industry 4.0 technologies/process-related characteristics and Lean practices through assigning each use case (260 German use cases have been studies) to a Lean principle. According to the results, two highest interdependences within the category of Industry 4.0 technologies and Lean principles have been identified between avoidance of waste and cloud computing and big data, respectively. In addition, their analysis reveals that the horizontal integration does not seem to have a high impact on the single principle of Lean concepts on the contrary to the common belief in the existing literature. The complete set of these interdependencies can guide manufacturers towards a better understanding of the implementation outcomes of each specific technology and also can be helpful with their decision-making processes.

Sanders et al. [34] enumerated the existing challenges regarding implementation of ten Lean manufacturing practices and summarized their proposed solutions through Industry 4.0 technologies. We have taken a relatively similar approach in enumerating the specific Lean practices and Industry 4.0 technologies that can be implemented to address the existing production challenges on the shop floor and managerial levels. Results are summarized in Table 1 below.

Obviously, there is not that much consistency among the aforementioned observations. This can be attributed mainly to the different underlying conditions and settings that these studies have been conducted on. These include socio-cultural factors, differences in the studied Lean practices and/or implemented Industry 4.0 technologies and also the performance metrics used during each research. In other words, any extrapolation of these research results to similar cases in terms of the effects of joint implementation of Industry 4.0 technologies and Lean practices has to carefully bear these caveats in mind.

3.2 Existing and/or potential integration of Industry 4.0 and Lean tools

This section reviews the existing systems in which a specific Industry 4.0 technology and a Lean tool have been hybridized as well as the current commercial systems or ongoing real-world projects in this discipline. These integrated systems mostly take advantage of various Industry 4.0 technologies to effectively digitize the Lean tools and techniques. The associated studies discuss the considerations that have to be taken into account while conducting this integration, as well as the operational benefits gained over the traditional systems.

Ma et al. [39] proposed an integrated framework for CPS-enabled (cyber-physical systems-enabled) smart Jidoka system. They introduced a distributed architecture that integrates service-oriented architecture, agent, function block (FB), cloud, and Internet of things to provide flexible configuration, deployment, and performance. The proposed smart Lean automation engine were implemented and tested on the engine assembly line of an automobile enterprise to handle the assembly of connecting rod bearing shell and main bearing shell and it proved to be effective especially in terms of cost reduction.

Mayr et al. [40] implemented a condition monitoring system for a stamping process. In this system, acquired sensor data is stored on cloud. The app Fleet Manager runs on the Siemens industrial cloud and allows the analysis of sensor data through data analytics methods. A graphical user interface (GUI) visualizes sensor data on mobile devices. Through this data analytics approach and human–machine interface platform, transparency for the operator will be significantly enhanced and warning notifications will be sent in case critical thresholds are exceeded for stamping force and tool wear. Cloud-based data storage allows for more effective data sharing within departments and dynamic scheduling of maintenance benefits. They also point out a potential digital twin-enabled dynamic VSM (value stream mapping) method using Siemens Plant Simulation software.

Dave et al. [41] proposed a framework for integration of recently developed IoT standards (specifically O-MI/O-DF (Open Messaging Interface/Open Data Format)) into the structure of emerging Lean construction management systems such as VisiLean in order to achieve enhanced real-time reporting of task status from the field, while improving interoperability between all major information systems and organizations throughout the construction project. They reported that this new approach can result in a more effective information flow, thus closing the loop between the head office to the site office to the field.

Table 1 Production challenges and specific helpful Industry 4.0 and Lean tools

Production challenge/problem	Lean tool/technique that can help	I4.0 technology that can help
Lot tracking	Kanban	Web/cloud Kanban, RFID tags, intelligent bins
Inventory control		RFID tags, NFC, QR codes, VR/AR
Machine failure	Poka yoke, Andon	Sensor/actuator, real-time data, cloud
Material handling		AGV, robot gripper
Resource sharing/collaborative design	–	Cloud, VR/AR
Overproduction	Kanban	
Quality control	Poka yoke, Jidoka	Big data, sensor/actuator
Leveled utilization	Heijunka	–
Long-term planning	Hoshin Kanri	Big data
Low utilization ratio of equipment	SMED, 5S	Robot gripper
Deficient product	Jidoka	Sensor/actuator
Seeking perfection	VSM, CI	Big data, real-time data
Worker training	Kaizen	VR/AR
Automatic purchase		

Chen and Chen [42] introduced a new real-time VSM enabled by RFID and wireless monitoring technologies. The system has been implemented in a disc assembly production and successfully generated a real-time VSM to management through automatic tracking of material flow. They reported that the new system saves time, reduces errors, and makes the VSM more visible to supervisors at any time which helps with making more accurate, real-time shop floor decisions. Another research work done by Meudt et al. [43] proposed a new framework called "VSM 4.0" in which classic VSM and an innovative data collection and handling system are integrated.

Wang [44] introduced an intelligent predictive maintenance system called IPdM using a set of Industry 4.0 technologies. In this system, data mining technique is applied on the data generated by CPS to capture any pattern that can indicate a possible fault. He reported that this system allows for early prediction of error and thus, corrective measures can be planned and introduced in the most effective way. Also, unplanned downtimes can be avoided and both staff and resources can be employed more effectively. According to the paper, the proposed system has already been successfully implemented within European, Norwegian, and Chinese industries and universities.

Würth Industrie Services GmbH & Co. KG [45, 46] introduced the optical order system iBin. A camera in the module detects the charging level of the bin and then status will be wirelessly reported to an inventory control system. Besides, iBin is also able to send orders automatically to suppliers. As a result, buffer stock can be reduced and spare parts can be scheduled in an order-oriented way.

Servan et al. [47] reported the results of the project "MOON" developed by AIRBUS Military. "MOON" uses 3D information from the industrial digital mock-up to generate assembly instructions and their deployment as an alternative to the conventional paper-based documentation by applying augmented reality technology. According to the paper, the downstream reuse of 3D information, generated at other stages of the product life cycle, provides a significant time saving benefit, both in creating and in maintaining assembly documentation. Additionally, AR (augmented reality) facilitates the use of industrial digital mock-up to show process information in visual format, making its interoperation easier for personnel. This leads to improved working conditions and minimizes the possibility of errors during the execution of processes, resulting in a Leaner production.

Stäubli Corp., Duncan, SC, https://www.staubli.com/en-us/ has demonstrated a new, fully automated quick-mold-change system that ensures a safe mold exchange within minutes. The system removes a mold from the injection press and replaces it with a preheated, production-ready tool. It lets processors with frequent mold changes prepare the next mold in parallel with ongoing production, moving towards the single-minute-exchange-of-die (SMED) concept. The smart mold loading table accurately adjusts its height for mold transfer through processing the data it receives from both the mold and the injection machine.

Aside from the aforementioned attempts in which specific integration frameworks were proposed and/or real-world implementations were reported, there are some other papers which present their ideas regarding potential integration of Industry 4.0 technologies and Lean practices or review other existing integrated systems. For instance, Kolberg et al. [48, 49] commented on how realization of four pillars of smart factory, namely “smart operator,” “smart product,” “smart machine,” and “smart planner” can contribute to more effective implementation of Lean principles. They also enumerated all the technologies that could contribute to realization of each of these pillars. In addition, they made an effort to come up with a common, unified communication interface for workstations to support the integration with Lean tools. Considering the excessive scattering of these ideas in the literature, we categorized the references based on the presented correlations among Lean tools and Industry 4.0 technologies in Table 2.

4 Use case: a cloud Kanban

In order to demonstrate a real-world example for integrating Industry 4.0 technologies and Lean tools, we present an EAT (estimated-actual-total) *Kanban* framework that has practical use in any dashboard-type monitoring of processes. In manufacturing engineering, the use of Kanban is mainly limited to the operations and specifically to controlling the WIP inventory. In software engineering, Kanban is used to manage user stories or software requirements. While these are useful for specific assembly line or product development, Kanban application fails to address an enterprise-wide view of resource management. To this end, we provide an enhanced platform that provides a holistic view of operations management using the cloud technology as one of the core Industry 4.0 technologies. This cloud-based decision support system (DSS), combined with a robust continuous improvement methodology, can help operation managers to make efficacious decisions. This framework is developed and implemented for a generic service operations management (SOM) organization, utilizing the power and innovative cloud platform Microsoft® Azure™.

4.1 Overview

We define Kanban as a visual tool to monitor and control resource consumption and production of an enterprise. Our proposed framework for Cloud Kanban, as one can see from Fig. 2 (left), consists of six foundational elements that can be switched on and off, scaled up and from any modern web browsers. The six elements include:

1. The license key for the system that determines the size and scale of the system (Service Plan)
2. The database holds the needed production, and planning data
3. A cloud-based server that has all the web pages and items (Application Server)
4. A user authentication system so end users can log in via the organization’s email credentials (The Active Directory, AD)
5. The User Interface that contains main menu and sub menus that need to be accessed by end users
6. The needed business rules to accomplish the data entry and reporting tasks (The Logic)

In our example, our active directory was user@cloudkanban.onmicrosoft.com, the database was a Microsoft SQL server, App service was Microsoft Azure Web Service, Service Plan was Microsoft Imagine, the User Interface was built in Model-View-Controller. Net Framework and the business logic was written in c#.

4.2 Implementation

In a typical service, there is a job order that constitutes multiple activities. As one can see from Fig. 2, the first step is to build the estimated total amount of the job and individual activities with the job. For all the activities ($n = 1, 2, 3$ to N)

Table 2 A matrix presenting existing literature containing integrated Lean tools and Industry 4.0 technologies

Lean tools/techniques I 4.0 technologies	Kanban (Pull)	Poka yoke	Andon	SMED	Jidoka	VSM	CI	Kaizen	TPM	Heijunka	5S
Big data	[50]	[51]		[34]			[52]		[36]		
RFID/identification	[31, 51]	[31]		[53]	[54]						
Cloud computing	[55, 56]	[51]					[56]		[52, 53]		
AR/VR											[31]
Sensor/actuator					[39]		[51]	[51]	[31]		
Real-time data	[51]		[54]		[54]	[43, 51]					
AGV											
Mobile electronics	[48]		[51]								
Wireless networks	[41, 48]				[39]	[43]	[51, 52]				
HMI		[31]			[54]			[34]	[34]	[48]	[53]

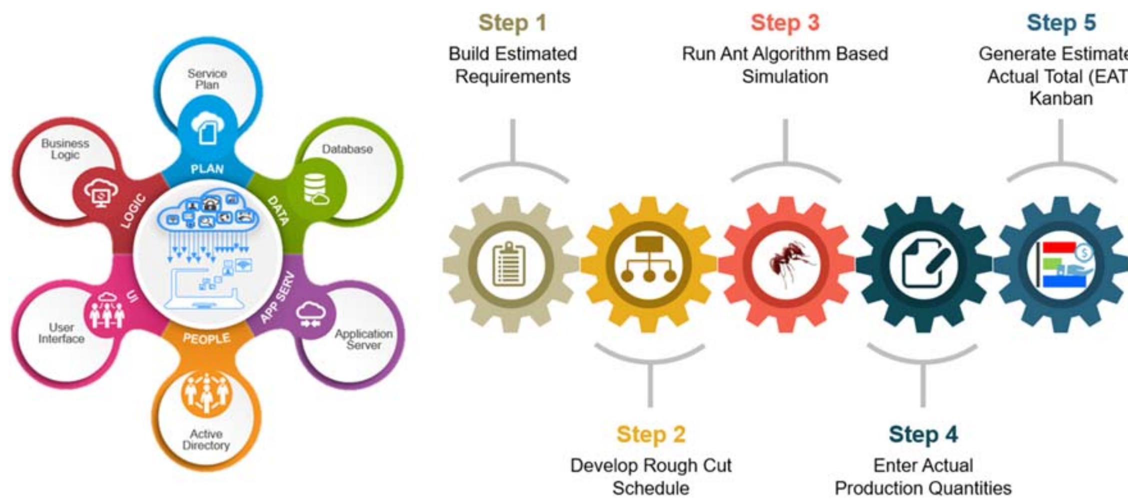
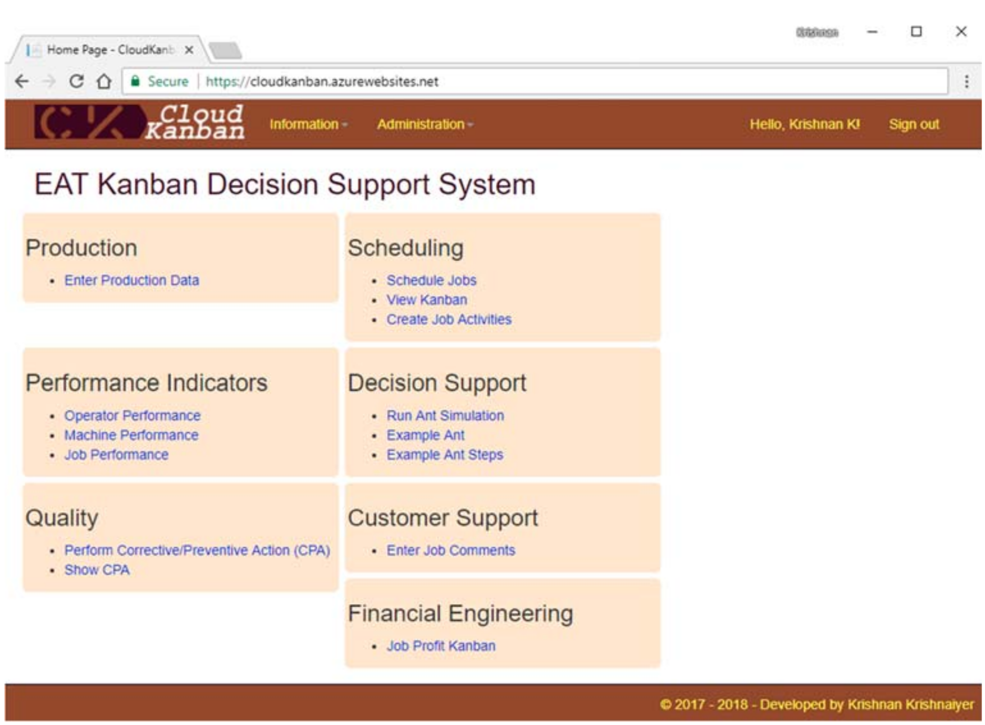


Fig. 2 Foundational elements of cloud Kanban (left). Implementation framework of cloud Kanban (right)

for the job, an estimated amount per shift ($s = 1$ to 3) is build. The amount per shift estimate is computed based on the "Standard Rate Per Hour" (SRPH) for the activity. The second is to establish a rough cut schedule. Typically, a "Capacity vs. Requirement" analysis is done based on the existing resources. Various factors such as number of machines available, number of employees and raw material availability are displayed. The third step is a decision support system simulation. For priority jobs, an ant algorithm-based simulation is run to understand the optimization feasibility of the rough cut schedules. Based on the results, if needed, fine tuning of rough cut schedules is performed. The fourth step is to gather the actual production quantities. The labor hours used, number of bad quality product, and production hours lost due to down time is also entered. Over time production data gathered helps to refine and set the SRPH. The final step is to the display the job and activity progress based on the estimated actual and total Kanban system [47]. Fig. 3 shows the main menu of the cloud-based Kanban system. The Kanban decision support system has features for entering production data and also an ant colony-based simulation for the schedulers to validate their rough cut capacity planning. There are seven modules (production, scheduling, performance indicators, decision support, system setup, quality, and customer service) in the

Fig. 3 Cloud Kanban



system. These can be completely customized based on the user roles [47].

5 Summary and conclusion

Ever increasing implementation of Industry 4.0 technologies in today's industry has attracted the interest of more researchers to study the link between these technologies and Lean manufacturing as the predominant paradigm of production environments over the last 20 years. Although there have been some research work exploring into this area, their attempts were mainly scattered and did not holistically address the topic with the necessary breadth and depth. In this paper, we have tried to provide a comprehensive review of the existing research work and identify the potential research gaps to guide and form future studies (Table 3). It can be concluded from the findings that in some cases, new work has to be done to keep up with the rapid development of these technologies. For instance, in a research discussing the effects of IT in achieving the principles of Lean production done by Riezebos et al. [33], only centralized IT systems have been considered, leaving out the more recent distributed structures resulting from cloud technologies. This distributed structure is more in line with the Lean philosophy in which team working is emphasized and responsibility and authority are delegated to the workforce. As a result, most of the contradictions between IT systems and Lean principles mentioned in this article will be no longer relevant in a cloud-based environment. It was also noticed that, while investigating the effects of simultaneous implementation of Industry 4.0 technologies and Lean practices on operational performance, technologies related to

Table 3 Summary of literature discussing interaction between Industry 4.0 technologies and Lean tools

Reference	Research type	Data set	Performance dimension	Contributions/findings
Tortorella et al. [30]	Quantitative	147 Brazilian manufacturers	Productivity, delivery service level, inventory level, quality, safety	- Technologies related to products or services effect the moderating effect positively - Process-related technologies moderate the effect of low setup time negatively - Effects might change when I4.0 practices are implemented simultaneously with Lean
Satoglu et al. [31]	Qualitative	–	–	- Industry 4.0 technologies solely cannot address the issues rooted in mismanagement or disorganization - An effective information flow is critical both before and after implementing I4.0 technologies
Khanchanapong et al. [32]	Quantitative	186 manufacturers in Thailand	Cost, product quality, lead-time, and flexibility	- A significant positive interaction effect exists between advanced manufacturing and Lean on cost, product quality, lead-time, and flexibility - Firms better off investing in both of these paradigms simultaneously
Riezebos et al. [33]	Qualitative	–	–	- Origins of the different approaches were similar - When the acceptance of Lean manufacturing became more pervasive, the practices typically converged into systems with combined concepts
Sanders et al. [34]	Qualitative			- Enumerated the existing challenges regarding implementation of ten Lean manufacturing practices and summarized the offered solutions through Industry 4.0 technologies
Wagner et al. [32]	Quantitative	Survey of 20 automotive industry project leaders	–	- Developed an impact matrix to identify Industry 4.0 solutions and Lean correlations - Assessed a cyber-physical Just-in-Time delivery solution based on their developed matrix
Azadeghan et al. [35]	Quantitative	126 US manufacturer	Complexity, dynamism	- "Environmental complexity" positively moderates the effects of Lean practices on operational performance
Dombrowski et al. [24]	Quantitative	260 German manufacturers	–	- Statistically disclosed that the digitalization has the highest impact on the principles of Lean - Horizontal integration does not seem to have a high impact on the single principles of Lean

products, services, and processes should not be tarred with the same brush, as there is differentiation among their moderating effects on various Lean practices [30]. Another point is that the socio-cultural factors also have to be taken into account while investigating the link between Industry 4.0 and Lean implementation, as different and sometimes contradicting results have been obtained studying companies from different countries, especially between companies located in developing counties such as Thailand and Brazil and western countries [30, 32]. In terms of new platforms integrating Industry 4.0 technologies and Lean tools, there is going to be a huge opportunity considering the explosive rate of improvements in the existing technologies and the emergence of new ones. The "Existing and/or potential integration of Industry 4.0 and Lean tools" section of this paper can be a good foundation for researchers to explore before moving towards new implementations. A cloud-based Kanban decision support system is also presented here as a real-world demonstrator for integrating an Industry 4.0 technology (cloud computing) and a major Lean tool (Kanban).

References

1. Womack JP, Jones DT, Roos D (1990) The machine that changed the world: the triumph of lean production. Rawson Macmillan, New York
2. Womack JP, Jones DT (1997) Lean thinking—banish waste and create wealth in your corporation. J Oper Res Soc 48(11):1148–1148
3. Knobloch J, Zühlke D (2017) Towards a lean automation interface for workstations AU - Kolberg, Dennis. Int J Prod Res 55(10): 2845–2856. https://doi.org/10.1080/00207543.2016.1223384
4. Dickmann P (2008) Schlanker Materialfluss: mit Lean production Kanban und innovationen, Springer-Verlag,
5. Strandhagen JO, Chan FTS (2018) The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda AU - Buer, Sven-Vegard. Int J Prod Res 56(8): 2924–2940. https://doi.org/10.1080/00207543.2018.1442945
6. Bouzary H, Chen FF, Krishnaiyer K (2018) A modified discrete invasive weed algorithm for optimal service composition in cloud manufacturing systems. Proc Manuf 17:403–410. https://doi.org/10.1016/j.promfg.2018.10.063
7. Kang HS, Lee JY, Choi S, Kim H, Park JH, Son JY, Kim BH, Noh SD (2016) Smart manufacturing: past research, present findings, and future directions. Int J Prec Eng Manuf-Green Technol 3(1): 111–128. https://doi.org/10.1007/s40684-016-0015-5
8. Zarreh A, Saygin C, Wan H, Lee Y, Bracho A, Nie L (2018) Cybersecurity analysis of smart manufacturing system using game theory approach and quantal response equilibrium. Proc Manuf 17: 1001–1008. https://doi.org/10.1016/j.promfg.2018.10.087
9. Bracho A, Saygin C, Wan H, Lee Y, Zarreh A (2018) A simulation-based platform for assessing the impact of cyber-threats on smart manufacturing systems. Proc Manuf 26:1116–1127. https://doi.org/10.1016/j.promfg.2018.07.148
10. Lasi H, Fettke P, Kemper H-G, Feld T, Hoffmann M (2014) Industry 4.0. Bus Inf Syst Eng 6(4):239–242. https://doi.org/10.1007/s12599-014-0334-4
11. Lu Y (2017) Cyber physical system (CPS)-based industry 4.0: a survey. J Ind Integr Manag 02(03):1750014. https://doi.org/10.1142/S2424862217500142
12. Hermann M, Pentek T, Otto B (2016) Design principles for Industrie 4.0 scenarios. In: 2016 49th Hawaii International Conference on System Sciences (HICSS), 5–8 2016. pp 3928–3937. doi:https://doi.org/10.1109/HICSS.2016.488
13. Trade G (2014) Invest (2016) Industrie 4.0—smart manufacturing for the future. Germany Trade & Invest, Berlin:1–40
14. Xu EL, Li L (2018) Industry 4.0: state of the art and future trends AU - Xu, Li Da. Int J Prod Res 56(8):2941–2962. https://doi.org/10.1080/00207543.2018.1444806
15. Sahba F, Sahba R (2018) Prevention of metro rail accidents and incidents in stations using RFID technology. In: 2018 World Automation Congress (WAC), 2018. pp 1–5. doi:https://doi.org/10.23919/WAC.2018.8430408
16. Sahba R A (2018) Brief study of software defined networking for cloud computing. In: 2018 World Automation Congress (WAC), pp 1–5. doi:https://doi.org/10.23919/WAC.2018.8430419
17. Bouzary H, Frank Chen F (2018) Service optimal selection and composition in cloud manufacturing: a comprehensive survey. Int J Adv Manuf Technol 97(1):795–808. https://doi.org/10.1007/s00170-018-1910-4
18. Montazeri M, Rao P (2018) Sensor-based build condition monitoring in laser powder bed fusion additive manufacturing process using a spectral graph theoretic approach. J Manuf Sci Eng 140(9):091002–091016. https://doi.org/10.1115/1.4040264
19. Montazeri M, Yavari R, Rao P, Boulware P (2018) In-process monitoring of material cross-contamination defects in laser powder bed fusion. J Manuf Sci Eng 140(11):111001–111019. https://doi.org/10.1115/1.4040543
20. Alaeddini A, Motasemi A, Faruqui SHA (2018) A spatiotemporal outlier detection method based on partial least squares discriminant analysis and area Delaunay triangulation for image-based process monitoring. IISE Trans 50(2):74–87. https://doi.org/10.1080/24725854.2017.1386336
21. Yao B, Imani F, Yang H (2018) Markov decision process for image-guided additive manufacturing. IEEE Robot Autom Lett 3(4): 2792–2798. https://doi.org/10.1109/LRA.2018.2839973
22. Marrey M, Malekipour E, El-Mounayri H, Faierson EJ (2019) A framework for optimizing process parameters in direct metal laser sintering (DMLS) using artificial neural network (ANN). EasyChair
23. Kranenburg Rv (2008) The Internet of Things: a critique of ambient technology and the all-seeing network of RFID. Insitute of Network Cultures,
24. Dombrowski U, Richter T, Krenkel P (2017) Interdependencies of Industrie 4.0 & Lean production systems: a use cases analysis. Proc Manuf 11:1061–1068. https://doi.org/10.1016/j.promfg.2017.07.217
25. Tarhani M, Kavian YS, Siavoshi S (2014) SEECH: scalable energy efficient clustering hierarchy protocol in wireless sensor networks. IEEE Sensors J 14(11):3944–3954. https://doi.org/10.1109/JSEN.2014.2358567
26. Li S, Rao SS, Ragu-Nathan TS, Ragu-Nathan B (2005) Development and validation of a measurement instrument for studying supply chain management practices. J Oper Manag 23(6):618–641. https://doi.org/10.1016/j.jom.2005.01.002
27. Staats BR, Brunner DJ, Upton DM (2011) Lean principles, learning, and knowledge work: evidence from a software services provider. J Oper Manag 29(5):376–390. https://doi.org/10.1016/j.jom.2010.11.005
28. Shah R, Ward PT (2007) Defining and developing measures of lean production. J Oper Manag 25(4):785–805. https://doi.org/10.1016/j.jom.2007.01.019

29. Pellerin R, Lamouri S, Tamayo-Giraldo S, Barbaray R (2018) The industrial management of SMEs in the era of Industry 4.0 AU - Moeuf, Alexandre. Int J Prod Res 56(3):1118–1136. https://doi.org/10.1080/00207543.2017.1372647
30. Tortorella G, Giglio R, van Dun DH (2018) Industry 4.0 as a moderator on the relationship between lean and operational performance. In: 25th International Annual EurOMA Conference: To serve, to produce and to servitize in the era of networks, big data and analytics
31. Satoglu S, Ustundag A, Cevikcan E, Durmusoglu MB (2018) Lean transformation integrated with Industry 4.0 implementation methodology. In: Industrial engineering in the Industry 4.0 era. Springer, pp 97-107
32. Khanchanapong T, Prajogo D, Sohal AS, Cooper BK, Yeung ACL, Cheng TCE (2014) The unique and complementary effects of manufacturing technologies and lean practices on manufacturing operational performance. Int J Prod Econ 153:191–203. https://doi.org/10.1016/j.ijpe.2014.02.021
33. Riezebos J, Klingenberg W, Hicks C (2009) Lean production and information technology: connection or contradiction? Comput Ind 60(4):237–247. https://doi.org/10.1016/j.compind.2009.01.004
34. 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. J Ind Eng Manag 9(3):811–833
35. Azadegan A, Patel PC, Zangoueinezhad A, Linderman K (2013) The effect of environmental complexity and environmental dynamism on Lean practices. J Oper Manag 31(4):193–212. https://doi.org/10.1016/j.jom.2013.03.002
36. Wagner T, Herrmann C, Thiede S (2017) Industry 4.0 impacts on Lean production systems. Proc CIRP 63:125–131. https://doi.org/10.1016/j.procir.2017.02.041
37. Dworschak B, Zaiser H (2014) Competences for cyber-physical systems in manufacturing–first findings and scenarios. Proc CIRP 25:345–350. https://doi.org/10.1016/j.procir.2014.10.048
38. Bouzary H, Frank Chen F (2018) A hybrid grey wolf optimizer algorithm with evolutionary operators for optimal QoS-aware service composition and optimal selection in cloud manufacturing. Int J Adv Manuf Technol 101:2771–2784. https://doi.org/10.1007/s00170-018-3028-0
39. Ma J, Wang Q, Zhao Z (2017) SLAE–CPS: smart lean automation engine enabled by cyber-physical systems technologies. Sensors 17(7):1500
40. 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. Proc CIRP 72:622–628. https://doi.org/10.1016/j.procir.2018.03.292
41. Dave B, Kubler S, Främling K, Koskela L (2016) Opportunities for enhanced lean construction management using Internet of Things standards. Autom Constr 61:86–97. https://doi.org/10.1016/j.autcon.2015.10.009
42. Chen JC, Chen K-M (2014) Application of ORFPM system for lean implementation: an industrial case study. Int J Adv Manuf Technol 72(5):839–852. https://doi.org/10.1007/s00170-014-5710-1
43. Meudt T, Metternich J, Abele E (2017) Value stream mapping 4.0: holistic examination of value stream and information logistics in production. CIRP Ann 66(1):413–416. https://doi.org/10.1016/j.cirp.2017.04.005
44. Wang K (2016) Intelligent predictive maintenance (IPdM) system–Industry 4.0 scenario. WIT Trans Eng Sci 113:259–268
45. Zuehlke D (2010) SmartFactory—towards a factory-of-things. Annu Rev Control 34(1):129–138. https://doi.org/10.1016/j.arcontrol.2010.02.008
46. Satoglu S, Ustundag A, Cevikcan E, Durmusoglu MB (2018) Lean transformation integrated with Industry 4.0 implementation methodology. In: Calisir F, Camgoz Akdag H (eds) Industrial engineering in the Industry 4.0 era. Springer International Publishing, Cham, pp 97–107
47. Servan J, Mas F, Menéndez J, Ríos J (2012) Assembly work instruction deployment using augmented reality. In: Key engineering materials. Trans Tech Publ, pp 25–30
48. Kolberg D, Knobloch J, Zühlke D (2017) Towards a Lean automation interface for workstations. Int J Prod Res 55(10):2845–2856
49. Kolberg D, Zühlke D (2015) Lean automation enabled by industry 4.0 technologies. IFAC-PapersOnLine 48(3):1870
50. Chen T, Lin YC (2017) Feasibility evaluation and optimization of a smart manufacturing system based on 3d printing: a review. Int J Intell Syst 32(4):394–413
51. Mrugalska B, Wyrwicka MK (2017) Towards Lean production in Industry 4.0. Proc Eng 182:466–473. https://doi.org/10.1016/j.proeng.2017.03.135
52. Hambach J, Kümmel K, Metternich J (2017) Development of a digital continuous improvement system for production. Proc CIRP 63:330–335. https://doi.org/10.1016/j.procir.2017.03.086
53. Karre H, Hammer M, Kleindienst M, Ramsauer C (2017) Transition towards an Industry 4.0 state of the LeanLab at Graz University of Technology. Proc Manuf 9:206–213. https://doi.org/10.1016/j.promfg.2017.04.006
54. Jing M, Qiang W, Zhibiao Z (2017) SLAE–CPS: smart Lean automation engine enabled by cyber-physical systems technologies. Sensors (14248220) 17(7):1500. https://doi.org/10.3390/s17071500
55. Krishnaiyer K, Chen FF (2017) A cloud-based Kanban decision support system for resource scheduling & management. Proc Manuf 11:1489–1494. https://doi.org/10.1016/j.promfg.2017.07.280
56. Krishnaiyer K, Chen FF, Bouzary H (2018) Cloud Kanban framework for service operations management. Proc Manuf 17:531–538. https://doi.org/10.1016/j.promfg.2018.10.093

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.