Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 72 (2018) 622–628

www.elsevier.com/locate/procedia

51st CIRP Conference on Manufacturing Systems

Lean 4.0 - A conceptual conjunction of lean management and Industry 4.0

A. Mayr[a,]*, M. Weigelt[a], A. Kühl[a], S. Grimm[b], A. Erll[a], M. Potzel[a], J. Franke[a]

[a] *Institute for Factory Automation and Production Systems, Friedrich-Alexander University Erlangen-Nuremberg, Fuerther Str. 246b, 90429 Nuremberg, Germany*
[b] *Siemens AG, Process Industries and Drives, Large Drives, Gugelstr. 74, 90459 Nuremberg, Germany*

* Corresponding author. Tel.: +49 911 5302-9064; fax: +49 911 5302-9070. E-mail address: andreas.mayr@faps.fau.de

Abstract

Applying lean can boost a firm’s performance significantly by focusing on value-adding activities. Additionally, Industry 4.0 is regarded as another promising trend in industry. Combining these developments resulted in terms like "lean 4.0". However, the existing literature lacks a comprehensive and detailed conjunction of both paradigms. This paper builds upon this research gap with a twofold aim: Firstly, the target is to build upon existing groundwork to conclude whether lean management and Industry 4.0 can complement each other. Secondly, this work considers how Industry 4.0 can support specific lean methods. This is exemplified by an electric drives production use case.

Keywords: Industry 4.0; lean management; production management; cyber physical systems; internet of things

1. Introduction

The capability to manufacture individual and personalized products is the key for success in a globalized and digitally connected world. Customers are used to receiving specifically fitted goods for their needs. These high customer expectations lead to an increase in variant diversity and intensify the complexity of the production environment [1].

One solution to this issue that reduces complexity within the industrial area is the Toyota Production System (TPS). This production philosophy developed by the Toyota Motor Corporation in the last century aims to reduce waste in the value chain in order to minimize lead time. By applying this ideology and permanently focusing on customer value in a continuous improvement process, Toyota was able to gain a world leading position in the automotive industry. Nowadays, the TPS is well known as lean management (LM) or lean manufacturing and widely deployed as a standard in various industries. [2, 3]

Another possibility to handle the increasing complexity in manufacturing is given by the relatively new research field Industry 4.0 (I4.0). It aims to improve transparency through the digital linkage of each element involved in the production. It is based on cyber-physical systems (CPS) which organize the value creation process by themselves. Another key feature of I4.0 is the realization of an internet of things (IoT) which allows a worldwide data communication in real time. [4]

Both production paradigms, i.e. LM & I4.0, are promising to solve future challenges in manufacturing. Hence, the question arises if and how these developments can possibly support each other. Thus, this paper aims to contribute to this research area. More precisely, the authors provide answers to the following research questions: How can LM and I4.0 supplement each other on a conceptual level? And which I4.0 tools can support specific lean methods?

Within this paper an initial overview on relevant groundwork is given and a proposal to link LM and I4.0 in a conceptual way is developed. Thereby, existing literature is classified in three research streams. Furthermore, it is shown how I4.0 tools can contribute to optimizing specific lean

10.1016/j.procir.2018.03.292

methods, namely just-in-time (JIT), heijunka, kanban, value stream mapping (VSM), total productive maintenance (TPM), single minute exchange of die (SMED), visual management (VM), and poka-yoke. This evolutionary approach to enhance lean methods will help scientists as well as practitioners to design a versatile production system for a constantly changing environment. Lastly, a use case on applying the machine learning-based condition monitoring (CM), as well as cloud computing to TPM exemplifies how both paradigms can act jointly to improve the production of electric drives. The authors conclude by discussing the developed concept and summarizing the key findings.

2. Preliminary work related to lean 4.0

Following Dombrowski et al., the existing literature is structured into two perspectives: Either LM is considered as a prerequisite for introducing I4.0 tools or I4.0 tools are regarded as promoters of LM [5]. Another widely acknowledged perspective is that the combination of both topics yields in positive synergies. This is added as a third, more general perspective. Table 1 gives an overview of literature which supports these perceptions. After outlining these three views limitations of extant research are analyzed.

Table 1. Existing perspectives on combing I4.0 and LM

Perspective	Authors
LM as enabler towards I4.0	[6, 7, 8, 9, 10, 11, 12, 13, 14, 15]
I4.0 advances LM	[16, 17, 18, 19, 20]
Positive correlation between LM & I4.0	[21, 22, 23]

2.1. Lean management as enabler towards Industry 4.0

Several authors name LM as a prerequisite for the successful introduction of I4.0 solutions [6, 7, 8]. This is supported by the hypothesis from Bill Gates that automating inefficient processes will magnify their inefficiency. Collectively the insights can be summarized as follows:

- Standardized, transparent, and reproducible processes are of fundamental significance for introducing I4.0 [6, 9, 10].
- Decision-makers require LM competence for considering customer value and avoiding waste [7].
- By reducing product and process complexity LM enables the efficient and economic use of I4.0 tools [6, 14].

Hence, lean processes are regarded as a basis for the efficient and economic implementation of I4.0. However, Nyhuis et al. annotate that LM and I4.0 implementation may influence each other iteratively. Thus, the progression is not necessarily purely sequential. [24]

2.2. Industry 4.0 advances lean management

Wagner et al. as well as Pokorni et al. describe that lean processes can be stabilized and refined by applying I4.0 [16, 17]. While Ruettimann et al. emphasize the ability to improve the flexibility of modern lean production systems, Kolberg and Zuehlke state that I4.0 can enhance LM [18, 19]. Hence, I4.0 contributes to addressing limitations of LM. Exemplary, the economic production of goods in a lot size of one is a way to enhance production economies beyond traditional economies of scale. Data in real-time improves transparency and information quality. [12] Moreover, I4.0 is promising to cope with a fluctuating market demand superior to a levelled production in LM. Eventually, the increased flexibility through I4.0 helps to cope with the rising complexity.

2.3. Correlation between lean management and Industry 4.0

Mrugalska and Wyrwicka support the statement that I4.0 and lean can coexist and support each other [23]. In accordance Vogel-Heuser et al. reject a contradiction between I4.0 and LM [22]. Moreover, committing into I4.0 can help to overcome existing barriers for implementing lean [21].

For combining LM and I4.0 the extant literature manifested terms like lean 4.0, lean automation, smart lean manufacturing, and lean industry 4.0. As elaborated, the majority of authors approve of the general compatibility of LM and I4.0. This perspective can be attributed to similarities concerning targets like the reduction of complexity, central pillars, and lean principles as a common ground (see Fig. 1). Accordingly, both paradigms are managed in a decentral way. Kanban in LM as well as self-organizing systems in I4.0 distribute responsibility in subsystems [6, 25]. Moreover, LM and I4.0 focus on a pivotal role of employees [6].

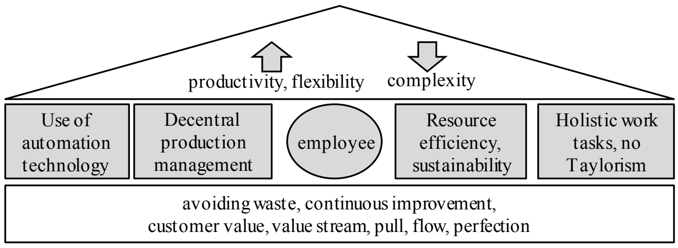

Fig. 1. Commonalities of LM and I4.0

2.4. Limitations of existing research approaches

Despite the analyzed linkage between the two topics, the literature research reveals several limitations. Hence, Kolberg and Zuehlke conclude that a common framework is lacking as concepts are discussed in an exemplified way without a structured approach [19]. Moreover, existing contributions were often found to address LM on a generic level. Hence, the reference to particular lean methods is often found to be missing. Solely Wagner et al. use a matrix to illustrate the impact of eight I4.0 tools on several lean principles which include specific methods [16]. However, only the influence of CPS on JIT is described in detail. Thus, this limits the transparency of the remaining evaluation. Building thereon, this paper addresses eight specific lean methods instead of basic principles like waste reduction. Moreover, a wider range of I4.0 tools is covered. Additionally, a critical discussion and consideration of limitations is often found to be absent.

This paper addresses the mentioned limitations by considering previously elaborated recommendations for a framework. Consequently, this work includes I4.0 tools that support LM as well as it provides applicable examples. [19]

3. Conceptual conjunction of I4.0 tools and lean methods

As a result of an extensive review of existing literature and reasonable assessments of the authors, Table 2 depicts a matrix to illustrate which I4.0 tools can be utilized to support the analyzed lean methods. The I4.0 tools are selected based on reviewing academic as well as corporate publications. Subsequently, the synergy potentials are elaborated in brief.

3.1. Just-in-time/just-in-sequence 4.0

The lean method JIT/just-in-sequence (JIS) aims to deliver the right product, at the right time, place and quality in the right quantity for the right costs. Several I4.0 tools can contribute to this objective as mentioned in Table 2.

Automated guided vehicles (AGV), for instance, can transport objects within the material flow automatically. This minimizes human mistakes as well as empty trips. Besides, material is supplied to workstations in accordance to the requirements. In case of obstacles the transportation system will reroute the vehicle to an alternative path. [25, 26]

Furthermore, intelligent bins and smart products also pursue self-optimization. A digital object memory stores every necessary manufacturing parameter. In combination with monitoring the condition of the transported goods, it is used to navigate the AGV efficiently. This self-organization helps to build robust logistics networks for production. [7]

In addition, Auto-ID technology, such as RFID, can be applied to track material in real-time and to localize objects in the value chain precisely. This results in reduced search time as well as improved process transparency. Additionally, part recognition allows the identification of incorrect components. Parts can then be removed, which contributes to the idea of poka-yoke. Moreover, the automated selection of RFID tags enables continuous stock monitoring which eventually results in reduced inventory levels. Besides, it facilitates an automated replenishment process from suppliers. [16, 27]

The JIT/JIS 4.0 method additionally applies big data and data analytics techniques. The opportunity to analyze detailed real-time process information provides insights into parameters, helps to identify trends, and allows to deduce rules for the production system [28]. Furthermore, a continuous material flow is supported by reducing machine downtimes through predictive maintenance actions [29]. In general, data analysis has the potential to contribute to an improved system performance of the whole supply chain [16].

Overall, JIT/JIS 4.0 convinces with higher transparency, shorter lead times and improved flexibility. Apart from this, supply chain actors benefit from a better cooperation and an improved resistance against disturbances.

3.2. Heijunka 4.0

The objective of heijunka is to level the production program to a constant rate. By solely producing the customer demand, waste in the form of overproduction is reduced.

Some I4.0 tools contribute to improving heijunka. Data analytics, for instance, enhances the forecast quality. Planning is stabilized by using data history in combination with a better understanding of customer needs through an in-depth analysis of the market. [7, 26] Besides, new software tools using advanced analytics can be utilized to support the planning process itself. For example, the software AnaPro levels the production program automatically based on product specification, structure of the technological process, workplace and sales [30].

Applying heijunka 4.0 benefits in a reduced effort for levelling the production program. Planning is automated and short-dated adjustments can be integrated smoothly.

3.3. Kanban 4.0

Kanban aims to retain a continuous material flow by maintaining a predefined stock level to guarantee an uninterrupted supply of material. I4.0 can contribute to enhancing this lean method.

Through simulation methods or a virtual real-time representation of physical objects based on a CAD model (digital twin), new kanban loops can be planned with more foresight and seamlessly integrated into the existing production environment. Simulation ensures the identification of ideal kanban parameters like lot size, stock or delivery frequency. Moreover, external changes can be included while the system refreshes parameters autonomously. [19]

By applying Auto-ID, a constant monitoring of work in process is possible. Hence, transparency of material movements is increased. This allows a comparison of target and actual values to remove unnecessary stock. [21] Additionally, a holistic linkage and improved exchange of data in production result in a self-organizing system. Thus, stock level can be reduced to a minimum.

Table 2. Combining I4.0 tools and lean methods

Lean methods / I4.0 tools	JIT/ JIS	Hei- junka	Kanban	VSM	TPM			SMED	VM			Poka- yoke
					1*	2**	3***		5 S	Zoning	Andon	
Additive manufacturing (AM)	x					x		x				
Plug and play							x	x				
Automated guided vehicles (AGV)	x		x									
Human-computer interaction (HCI)			x	x	x				x	x	x	x
Virtual representation (e.g. VR, AR)	x				x			x	x	x		x
Intelligent bins	x		x									
Auto-ID	x		x	x	x			x	x	x		x
Digital object memory	x				x			x				x
Digital twin/simulation	x	x	x	x		x	x	x	x			
Cloud computing	x			x	x	x						x
Real-time computing	x	x	x	x	x	x	x	x	x	x	x	x
Big data & data analytics	x	x	x	x		x						x
Machine learning				x	x			x				x

* autonomous maintenance, ** planned maintenance, *** early product and equipment management

The application of AGV can further contribute to a JIT delivery to the workplace. Refill arrives in the exact moment when new material is required. Consequently, the material supply at shop floor level can be realized by using a one-container-system. [25] Hence, the need to fill several containers with the same material is omitted.

To summarize the value of the kanban 4.0 method, the authors conclude that by applying I4.0 tools, stock levels can be minimized and transparency will increase. In consequence, the required space drops which ultimately results in cost savings. Besides, reduced inventory simplifies the detection of bottlenecks in the production processes. Therefore, causes of problems can be identified and encountered.

3.4. Value stream mapping 4.0

VSM enhances the transparency of the material and information flow within the value creation chain to identify waste. Subsequently, an improved target state is defined in value stream design. This optimization is aimed at shortening lead time and facilitating a flow through production. [31]

I4.0 leads to a connected manufacturing environment where data can be transmitted in real-time. While applying Auto-ID enables the instant localization of objects, big data and data analytics facilitate the consolidation of information. Consolidated key performance indicators enable decision making based on facts. [26] By deploying human-computer interaction (HCI) devices which allow to receive information, trigger actions and control processes (e.g. tablet, smartphone, and head mounted displays) information becomes remotely retrievable for stakeholders. Machine performance, for instance, can be analyzed by maintenance staff to reduce downtime or used by managers to pursue process optimization. Hereby, VSM 4.0 is a tool for daily operations management. Machine learning and data analytics support the creation of a value stream design. Target states are generated automatically and validated before implementation. [29] This approach supports a continuous improvement process.

The main benefit of VSM 4.0 is the improvement in transparency through a real-time display of value streams. This helps in identifying waste within production processes and leads to a lean value creation. Besides, the effort to carry out VSM is reduced and decisions are based on real-time data.

3.5. Total productive maintenance 4.0

Smart factories result in an increasing number of maintenance objects. Additionally, their technical complexity is rising and an unplanned breakdown results in high costs [32, 33]. Hence, this paper focuses on the maintenance related pillars of total productive management which is meanwhile considered as a comprehensive management system. Foremost, autonomous maintenance shifts responsibility and authority for routine maintenance tasks from technicians to operators. The resulting free capacity of maintenance experts is tied to performing preventive maintenance measures (planned maintenance). Moreover, shorter product lifecycles, higher product variety and increasing product complexity account for a rising amount of production start-ups. Consequently, early equipment management refers to the introduction of new products and aims at realizing short ramp-up periods. [34, 35]

Several I4.0 tools support operators in taking on more responsibility. Especially the combination of virtual representation technologies like virtual reality (VR) and augmented reality (AR) as well as head-mounted displays facilitates training as well as maintenance instructions. [36] As maintenance typically involves non-recurring and context-sensitive activities, interaction with maintenance experts becomes crucial. By displaying virtual elements operators can be guided remotely [37]. Moreover, smart products and CM technology allow for load, wear, and defects to be monitored during machine operation. The early detection, isolation, and identification of faults results in less downtime and prevention of consequential damages. [38]

Based on cross-linked machines predictive analytics is a helpful tool for planned maintenance as it allows to analyze the correlation between condition parameters and the probability of defaults. Unlike conventional CM, predictive analytics uses complex algorithms to predict defects based on large data sets (big data). Eventually, predictive analytics is expected to scale up the accuracy of lifetime expectancy prognosis. [39] Lucke et al. propose a smart maintenance system to increase availability and to reduce maintenance costs as well as energy consumption [32].

In early product and equipment management, digitalization can contribute to eliminating media discontinuity between the planning and design phases on the one hand and the production phase on the other hand. Plug and play allows the autonomous integration of a technical system based on a modular design and a service-oriented architecture. Thus, production plants can easily be adapted and customized. The services are provided via standardized interfaces and operate independently of hardware-specific characteristics. [15, 40] Moreover, virtual commissioning contributes to a fast start-up curve as digital twins allow a realistic simulation of production plants. More precisely, hardware-in-the-loop simulation enables testing of real PLC code on real controls against a simulated plant model. [41, 42]

3.6. Single minute exchange of die 4.0

SMED aims at reducing downtime and cost caused by setup processes. Increased flexibility through short setup times facilitates the production of small lot sizes while achieving short lead times and maintaining a low level of stock. This becomes especially important as the amount of product variants is evolving. [43]

Nyhuis et al. identify I4.0 technologies for information transfer and provision as enablers for a lot size of one. Nevertheless, they reject a general linkage between I4.0 and a lot size of one based on the differentiation between digital and physical setup activities. While I4.0 provides a considerable potential for optimizing the former, physical setup times generally remain. [24]

Apart from AR and plug and play, additive manufacturing (AM) is expected to achieve the highest impact on setup time. Because AM processes are not product-specific, varying work-pieces can be produced with minimum setup times. Times for selection, search and adjustment of tools and work-pieces are omitted. Nevertheless, small adaptions, temperature adjustments and cleaning operations will still incur. Hence, Feldmann and Gorji argue that SMED can also be applied to AM. However, as setup times are already technologically reduced to a minimum, the impact is expected to be rather small. [44]

Overall, neither the methodological approach, nor the philosophical principles are questioned through I4.0 [38]. As a whole, SMED will remain of fundamental importance for reducing the physical setup time.

3.7. Visual management 4.0

The purpose of VM is to enhance transparency. Thus, deviations can be recognized at an early stage to implement countermeasures accordingly. This is achieved by transferring targets, standards, and specifications into a visual representation. The importance of VM is rising as the amount of available data increases. Methods for implementing VM are 5S, zoning and andon. [45]

5S is a systematic approach to organize the workplace and aims at improving clarity through keeping the workspace clean and arranging tools in a reasonable way. Hence, waste is eliminated on workplace level. Auto-ID and AR can assist in carrying out 5S more efficiently. RFID ensures the identification and the localization of objects which reduces search time. [27] Moreover, RFID tags can store instructions for cleaning tools and objects appropriately. Applying AR may replace physical shadow boards, as virtual elements guide operators where to place tools. Moreover, integrating gamification through AR might motivate personnel by gaining credits for cleaning or placing tools correctly. [46]

Zoning allows marking destinations by using visual means. This includes paths, manufacturing cells, and departments. A company-wide utilization of colors increases the information value. [45] Zoning implies several drawbacks. Firstly, signs and tapes must be adjusted physically. Secondly, this concept is not suitable for flexible navigation. HCI and AR help to overcome this lacking flexibility. Building upon Koch et al., Neges et al. describe a system for navigation by means of AR which is based on natural markers like warning signs [47, 48]. Alternatively, RFID can be used for indoor navigation, however, compared to Wi-Fi or Bluetooth, it is not commonly installed on smartphones and tablets. [49]

Andon is applied for visualizing status and disruptions in production and thus supports the lean principle jidoka. Additionally, andon boards display actual and target values to reveal deviations. [45] Unlike traditional andon lamps HCI devices like tablets, smartphones, head-mounted displays and smart watches enable a targeted notification for users. Hence, notifications are displayed in real-time regardless of the distance between operator and machine. Smart watches allow to assess the need for action with a glance at the operator's wrist [19, 23].

For digital andon boards, several suppliers provide solutions to visualize complex data and processes in real-time. Examples of relevant data are machine condition, production progress, order status and capacity utilization. Retrieving this information from mobile devices supports a location-independent access and use.

3.8. Poka-yoke 4.0

Poka-yoke describes mechanisms that help operators to avoid mistakes. Hence, it fosters the detection and elimination of abnormal conditions to prevent defective products from leaving the process. This is especially important in industries with a wide variety of products. Poka-yoke is either realized by generating forced sequences or by reviewing the process during its execution and stoppage in the event of errors. [50]

Auto-ID ensures the correct identification and assignment. A digital product memory allows to request required components and helps to identify incorrect deliveries. This prevents adding value to defective parts. [23] By using smart sensors and machine learning, machines can automatically adjust to irregularities to ensure optimal product quality. [51] Eventually, AR and head-mounted displays, as well as RFID-readers can be used to achieve zero-error picking. [52, 53] Despite the fact that strictly speaking CM is not a test method, Lettau describes the use of CM measurement technology for the end-of-line-test of electric drives production. [54]

4. Use case: CM and cloud computing in TPM

Currently, automation and mobility are popular examples which highlight the growing importance of electric drives. As the electric drives production is facing a rising cost pressure, ensuring high availability is of key importance. Various authors have examined the use of CM to reduce downtime. Examples include both thermo crimping [55] and ultrasonic crimping [56]. The following sections outline how CM and cloud computing contribute to facilitating maintenance of a sheet metal stamping press. In the electric drives production, stamped sheets are subsequently stacked and packetized to build the laminated core. While laser cutting is limited to small batches due to high energy costs, stamping is the preferred technology in series production. [57]

By default, stamping machines are equipped with sensors to capture the overall machine condition. This includes:

- measurement of rpm of the main drive,
- measurement of cutting pressure (current vs. maximum),
- identification of the used tools, and
- number of stamped sheets (actual vs. target).

As tooling costs for stamping are on a high level, machine downtime is critical. In theory, the acquired data allows avoiding scrap and tool damage. In the presented case of an industrial partner, however, sensor data has so far only been stored in local Microsoft Access or Microsoft Excel databases. Until now, no information about machine data is exchanged between departments.

The aim is to reduce downtime and predict imminent machine or tool damage. This leads to improved quality and reduced scrap or rework. As machine data is currently not visualized, the intention is to create data transparency for operators as well as maintenance experts on-site (gemba principle).

By applying a CM system, acquired sensor data is transmitted to and consolidated in a central database. The app fleet manager runs on the Siemens industrial cloud and allows the analysis of sensor data based on historical data and statistics. A graphical user interface (GUI) visualizes sensor data on mobile devices. The basic architecture of the CM system is shown in Fig. 2, whereas Fig. 3 illustrates the real control panel in front of the stamping machine. By visualizing machine parameters transparency for the operator is significantly enhanced. As a result of measuring the stamping force, tool wear is monitored. Warning notifications are created when critical thresholds are exceeded. Hence, the probability of machine damage is reduced. As data is stored in a central cloud, information can be forwarded to other departments. While spare parts management can prepare replacements in a timely manner, detailed planning benefits as maintenance activities can be scheduled dynamically.

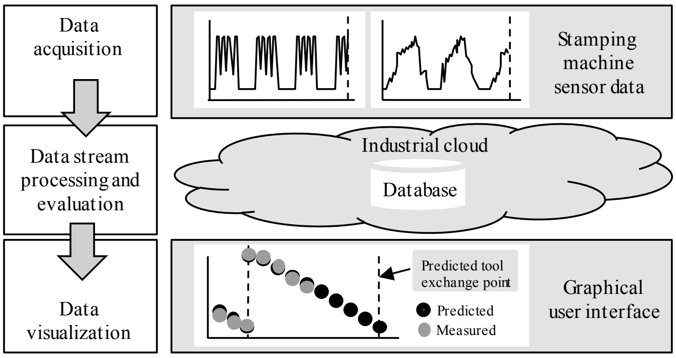

Fig. 2. Basic architecture of the CM system

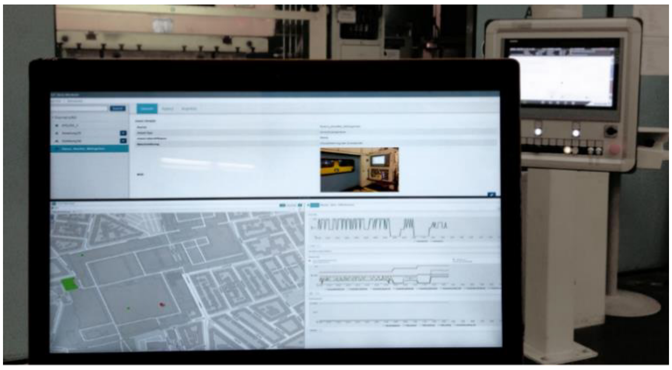

Fig. 3. GUI and stamping machine at Siemens AG (courtesy of Siemens AG)

5. Outlook: Digital twin enables dynamic VSM

Beyond the elaborated use case in section 4, another promising, not yet implemented conception is the integration of a digital twin to improve VSM. As an example, the software Siemens Plant Simulation digitally supports VSM while reducing required efforts. Beyond analyzing the current situation, the software provides recommendations for process optimization in form of a value stream design. However, this approach still lacks the implication of dynamic factors. Hence, it must be refined in the age of digitalization. [58, 59]

The integration of a digital twin replicating the whole manufacturing system is promising as it links the existing system in real-time to a digital reflection. In turn, this reflection can be used to build a value stream map based on real-time information instead of using stochastic models. This allows to overcome the static character of VSM as dynamic changes are considered. The model could refresh in an event-driven way, e.g. based on CM data (see section 4). Hence, detailed planning becomes more predictable and reliable.

6. Discussion

The success of introducing I4.0 technologies depends on several factors including usability, selective provision of information, acceptance of users, consideration of ethical, legal and social impacts and profitability. Hence, the use of I4.0 tools should be well-considered and gauged against process improvements. [25]

Besides, the presented lean methods 4.0 (see section 3) should not be seen as single tools for cost reduction. If I4.0 tools are implemented as stand-alone solutions, they might offer an additional value compared to status quo. However, the integration in an overall concept will be missed [60]. Similar to LM, lean 4.0 requires the implementation of a philosophy that aims at perfection in all daily activities by considering benefits from I4.0 tools [61].

7. Summary

This paper outlines various perspectives of a conjunction between LM and I4.0. In summary, the authors conclude that LM and I4.0 supplement each other on a conceptual level. Building on this perception, this paper outlines how various I4.0 tools can support eight lean methods. The findings reveal that applying I4.0 tools can assist in realizing the persecution of lean targets. A matrix visualizes which I4.0 tools support the analyzed lean methods in a condensed way.

A use case exemplifies how CM and cloud computing contribute to enhancing TPM for a sheet metal stamping press in the electric drives production. Additionally, an outlook further sketches how digital twins contribute to overcoming the static character of VSM.

Beyond the technical challenges future research should concentrate on how to implement lean 4.0 as a holistic concept. One key area is the integration of employees to avoid replicating failures from the introduction of computer-integrated manufacturing. Moreover, trade-offs and goal conflicts provide a promising avenue for future research.

References

[1] E. Westkämper, D. Spath, C. Constantinescu and J. Lentes (ed.), Digitale Produktion. Berlin/Heidelberg, Germany: Springer Berlin Heidelberg, 2013.

[2] J. P. Womack, D. T. Jones and D. Roos, Die zweite Revolution in der Autoindustrie: Konsequenzen aus der weltweiten Studie aus dem Massachusetts Institute of Technology, 6th ed. Frankfurt am Main/New York, Germany/NY, USA: Campus Verlag, 1991.

[3] G. Schuh, Lean Innovation. Berlin/Heidelberg, Germany: Springer Berlin Heidelberg, 2013.

[4] Bundesministerium für Wirtschaft und Energie, "Was ist Industrie 4.0?," plattform-i40.de, 2017. [Online]. Available: http://www.plattform-i40.de/I40/Navigation/DE/Industrie40/WasIndustrie40/was-ist-industrie-40.html [Accessed: Oct. 02, 2017].

[5] U. Dombrowski, T. Richter and P. Krenkel, "Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis," Procedia Manufacturing, vol. 11, pp. 1061–1068, 2017.

[6] W. Huber, Industrie 4.0 in der Automobilproduktion: Ein Praxisbuch. Wiesbaden, Germany: Springer Vieweg, 2016.

[7] H. Künzel (ed.), Erfolgsfaktor Lean Management 2.0: Wettbewerbsfähige Verschlankung auf nachhaltige und kundenorientierte Weise. Berlin/Heidelberg, Germany: Springer Gabler, 2016.

[8] D. Ketteler and C. König, Lean 4.0 – Schlank durch Digitalisierung. Frankfurt am Main, Germany: BearingPoint GmbH, 2017.

[9] Staufen AG (ed.), 25 Jahre Lean Management: Lean gestern, heute und morgen. Köngen, Germany: Staufen AG, 2016.

[10] R. Köther (ed.) and K.-J. Meier (ed.), Lean Production für die variantenreiche Einzelfertigung: Flexibilität wird zum neuen Standard. Wiesbaden, Germany: Springer Fachmedien Wiesbaden, 2017.

[11] B. Wang, J. Zhao, Z. Wan, J. Ma, H. Li and J. Ma, Lean Intelligent Production System and Value Stream Practice. 2016.

[12] J. Metternich, M. Müller, T. Meudt and C. Schaede, "Lean 4.0 - zwischen Widerspruch und Vision," ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 112, no. 5, pp. 346–348, 2017.

[13] O. Quasdorff and U. Bracht, “Die Lean Factory,” ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 111, no. 12, pp. 843–846, 2016.
[14] W. Bick, “Warum Industrie 4.0 und Lean zwingend zusammengehören,” VDI-Z, vol. 156, no. 11, pp. 46-47, 2014.
[15] D. Zühlke, “SmartFactory—Towards a factory-of-things,” Annual Reviews in Control, vol. 34, no. 1, pp. 129–138, 2010.
[16] T. Wagner, C. Herrmann and S. Thiede, “Industry 4.0 Impacts on Lean Production Systems,” Procedia CIRP, vol. 63, pp. 125–131, 2017.
[17] B. Pokorni et al., “Produktionsassessment 4.0,” ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 112, no. 1-2, pp. 20–24, 2017.
[18] B. G. Rüttimann and M. T. Stöckli, “Lean and Industry 4.0—Twins, Partners, or Contenders? A Due Clarification Regarding the Supposed Clash of Two Production Systems,” Journal of Service Science and Management, vol. 9, no. 6, pp. 485–500, 2016.
[19] D. Kolberg and D. Zühlke, “Lean Automation enabled by Industry 4.0 Technologies,” IFAC-PapersOnLine, vol. 48, no. 3, pp. 1870–1875, 2015.
[20] D. Spath, O. Ganschar, S. Gerlach, M. Hämmerle, T. Krause and S. Schlund, Produktionsarbeit der Zukunft – Industrie 4.0. Stuttgart, Germany: Fraunhofer Verlag, 2013.
[21] A. Sanders, C. Elangeswaran and J. Wulfsberg, “Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing,” Journal of Industrial Engineering and Management, vol. 9, no. 3, pp. 811, 2016.
[22] B. Vogel-Heuser (ed.), T. Bauernhansl (ed.) and M. ten Hompel (ed.), Handbuch Industrie 4.0 Bd.4: Allgemeine Grundlagen, 2nd ed. Berlin/Heidelberg, Germany: Springer Vieweg, 2017.
[23] B. Mrugalska and M. K. Wyrwicka, “Towards Lean Production in Industry 4.0,” Procedia Engineering, vol. 182, pp. 466–473, 2017.
[24] P. Nyhuis, M. Schmidt and M. Quirico, “Mythos PPS 4.0,” in Handbuch Industrie 4.0: Geschäftsmodelle, Prozesse, Technik, G. Reinhart, Ed. München, Germany: Hanser, 2017, pp. 45–50.
[25] S. Kaspar and M. Schneider, “Lean und Industrie 4.0 in der Intralogistik: Effizienzsteigerung durch Kombination der beiden Ansätze,” Productivity Management, vol. 5, pp. 17–20, 2015.
[26] T. Bauernhansl (ed.), M. Hompel (ed.) and B. Vogel-Heuser (ed.), Industrie 4.0 in Produktion, Automatisierung und Logistik: Anwendung, Technologien, Migration. Wiesbaden, Germany: Springer Vieweg, 2014.
[27] N. Fescioglu-Unver, S. Choi, D. Sheen and S. Kumara, “RFID in production and service systems: Technology, applications and issues,” Information Systems Frontiers, vol. 17, no. 6, pp. 1369–1380, 2015.
[28] K. Ding and P. Jiang, “RFID-based production data analysis in an IoT-enabled smart job-shop,” IEEE/CAA Journal of Automatica Sinica, pp. 1–11, 2017.
[29] G. Srinivasan and G. Ganesh Prasad, “The role of Intelligent Automation, Big Data and Internet of Things in Manufacturing - A Survey,” Imperial Journal of Interdisciplinary Research, vol. 3, no. 5, pp. 934-940, 2017.
[30] K. Zywicki, P. Rewers and M. Bozek, “Data Analysis in Production Levelling Methodology,” in Recent Advances in Information Systems and Technologies, Á. Rocha, A. M. Correia, H. Adeli, L. P. Reis and S. Costanzo, Ed. Cham, Switzerland: Springer International Publishing, 2017, pp. 460-468.
[31] T. Meudt, M. P. Rößler, J. Böllhoff and J. Metternich, “Wertstromanalyse 4.0,” ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb vol. 111, no. 6, pp. 319-323, 2016.
[32] D. Lucke, M. Defranceski and T. Adolf, “Cyberphysische Systeme für die prädikative Instandhaltung,” in Handbuch Industrie 4.0 Bd.1: Produktion, B. Vogel-Heuser, T. Bauernhansl and M. Hompel (ed.), 2nd ed. Berlin, Germany: Springer Vieweg, 2017, pp. 75–91.
[33] Acatech (ed.), Smart Maintenance für Smart Factories: Mit intelligenter Instandhaltung die Industrie 4.0 vorantreiben. München, Germany: Herbert Utz Verlag, 2015.
[34] C. May and P. Schimek, Total Productive Management: Grundlagen und Einführung von TPM - oder wie Sie Operational Excellence erreichen, 3rd ed. Ansbach, Germany: CETPM Publishing, 2015.
[35] J. Schlick, P. Stephan, M. Loskyll and D. Lappe, “Industrie 4.0 in der praktischen Anwendung,” in Handbuch Industrie 4.0 Bd.2: Automatisierung, B. Vogel-Heuser, T. Bauernhansl and M. Hompel (ed.). Berlin, Germany: Springer Vieweg, 2016, pp. 3–29.
[36] R. Palmarini, J. Erkoyuncu, R. Roy and H. Torabmostaedi, “A systematic review of augmented reality applications in maintenance,” Robotics and Computer-Integrated Manufacturing, vol. 49, pp. 215–228, 2018.
[37] S. Benbelkacem et. al., “Augmented Reality Platform for Collaborative E-Maintenance Systems,” in Augmented Reality - Some Emerging Application Areas, A. Y. C. Nee, Ed. London, UK: InTech, 2011.
[38] A. Jardine, D. Lin and D. Banjevic, “A review on machinery diagnostics and prognostics implementing condition-based maintenance,” Mechanical Systems and Signal Processing, vol. 20, no. 7, pp. 1483–1510, 2006.
[39] A. Kieviet, “Digitalisierung der Wertschöpfung: Auswirkung auf das Lean Management,” in Erfolgsfaktor Lean Management 2.0: Wettbewerbsfähige Verschlankung auf nachhaltige und kundenorientierte Weise, H. Künzel, Ed. Berlin/Heidelberg, Germany: Springer, 2016, pp. 41–59.
[40] L. Dürkop and J. Jasperneite, “"Plug & Produce" als Anwendungsfall von Industrie 4.0,” in Handbuch Industrie 4.0 Bd.2: Automatisierung, B. Vogel-Heuser, T. Bauernhansl and M. Hompel (ed.). Berlin, Germany: Springer Vieweg, 2016, pp. 59–71.
[41] VDI-Guideline 3693: Virtuelle Inbetriebnahme. 2016.
[42] F.-F. Lacour, Modellbildung für die physikbasierte Virtuelle Inbetriebnahme materialflussintensiver Produktionsanlagen. München, Germany: Herbert Utz Verlag, 2012.
[43] B. Teeuwen and A. Grombach, SMED: Die Erfolgsmethode für schnelles Rüsten und Umstellen, 2nd ed. Herrieden, Germany: CETPM Publishing, 2015.
[44] C. Feldmann and A. Gorj, 3D-Druck und Lean Production: Schlanke Produktionssysteme mit additiver Fertigung. Wiesbaden, Germany: Springer Fachmedien, 2017.
[45] P. Gorecki and P. Pautsch, Praxisbuch Lean Management: Der Weg zur operativen Excellence, 2nd ed. München, Germany: Hanser, 2014.
[46] P. Pötters, I. Kloeckner and B. Leyendecker, “Gamification in der Montage,” ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, vol. 112, no. 3, pp. 163–167, 2017.
[47] M. Neges, C. Koch, M. Koenig and M. Abramovici, “Combining visual natural markers and IMU for improved AR based indoor navigation,” Advanced Engineering Informatics, vol. 31, pp. 18–31, 2017.
[48] C. Koch, M. Neges, M. Koenig and M. Abramovici, “Performance Study on Natural Marker Detection for Augmented Reality Supported Facility Maintenance,” Australasian Journal of Construction Economics and Building - Conference Series, vol. 2, no. 1, pp. 23-34, 2014.
[49] H. A. Karimi, Indoor wayfinding and navigation. Boca Raton, FL, USA: CRC Press, 2015.
[50] F. Brunner, Japanische Erfolgskonzepte: KAIZEN, KVP, Lean Production Management, Total Productive Maintenance, Shopfloor Management, Toyota Production System GD3 - Lean Development, 2nd ed. München, Germany: Hanser, 2011.
[51] J. Michels, “Praxisbeispiel: Intelligente Feldgeräte und selbstkorrigierende Fertigung,” in Industrie 4.0 im internationalen Kontext: Kernkonzepte, Ergebnisse, Trends, R. Heinze, C. Manzei and L. Schleuper, Ed. Berlin, Germany: Beuth, VDE Verlag GmbH, 2016, pp. 162–166.
[52] T. Rammelmeier, S. Galka and W. Günther, “Fehlervermeidung in der Kommissionierung,” in Logistics Journal Proceedings, 2012, pp. 1-8.
[53] W. Günther and M. Wölfle, Papierlose Produktion und Logistik. München, Germany: fml – Lehrstuhl für Fördertechnik Materialfluss Logistik Technische Universität München, 2011.
[54] U. Lettau, “Condition Monitoring für die Akustikprüfung,” Fertigungs- und Maschinenautomation, vol. 5, 2013.
[55] H. Fleischmann et al., “Distributed condition monitoring systems in electric drives manufacturing,” in 6th International Electric Drives Production Conference (EDPC), Nuremberg, 2016.
[56] A. Mayr et. al., “Potentials of Machine Learning in Electric Drives Production Using the Example of Contacting Processes and Selective Magnet Assembly,” in 7th International Electric Drives Production Conference (EDPC), Wuerzburg, 2017.
[57] A. Kamker and C. Nowacki, Elektromobilproduktion. Berlin, Germany: Springer Vieweg, 2014.
[58] H. Brügemann and P. Müller, “Digitales Wertstromdesign,”. in Advances in Simulation for Production and Logistics Applications, M. Rabe, Ed. Stuttgart, Germany: Fraunhofer IRB Verlag, 2008, pp. 575-584.
[59] S. Weyer et al., “Future Modelling and Simulation of CPS-based Factories: An Example from the Automotive Industry,” IFAC-PapersOnLine, vol. 49, pp. 97-102, 2016.
[60] N. Graef, “Industrie 4.0-Gesamtkonzept: Zusammenspiel von intelligenten Infrastrukturen, Paradigmen und technologischen Komponenten,” in Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis, A. Roth, Ed. Berlin/Heidelberg, Germany: Springer Gabler, 2016, pp. 73-82.
[61] M. Börkircher, H. Frank, R. Gärtner, F. Hasse, T. Jeske, F. Lennings, B. Schniering, H. P. Spaniol, S. Stowasser, M.-A. Weber, K.-H. Wintergerst, F. Wüseke, “Digitalisierung & Industrie 4.0: So individuell wie der Bedarf - Produktivitätszuwachs durch Informationen,” Düsseldorf.