IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Industry 4.0 Impacts on Lean Production Systems

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Abstract

The fourth industrial revolution and its Industry 4.0 or connected industry technologies dominate the current production research discussion. Digital developments like cyber-physical Systems are the key technologies for future, more agile production systems, but a common understanding of the term Industry 4.0 is not established now. First generic implementation approaches present manifold technical solutions but need to be integrated with existing Lean Production Systems. The actual impact of Industry 4.0 solutions is mostly not specified, and a method to evaluate is missing.

This paper introduces Industry 4.0 in an environment of connectivity in the Internet of Things and Services with the vision of a smart factory. Lean Production Systems and Lean Principles characterize the initial situation of industrial companies. Industry 4.0 offers an estimated benefit for companies by stabilizing Lean processes with Industry 4.0 applications. To support the development process the presented Concept of an Industry 4.0 impact matrix on lean production systems gives a useable framework. The matrix considers elements of lean production systems with Industry 4.0 technologies and estimates impact first. In the described development process of a cyber-physical Just-in-Time delivery, the matrix is used to find a stabilizing application for a Just-in-Time material supply process.

1. Introduction

A production system is a sociotechnical system that transforms inputs into outputs through value-adding processes as part of the transformation process (NY Quist et al. Citation 2008). Inputs include materials and used energy, as well as the necessary financial resources and the know-how employed. Outputs include the resulting products and other residual materials. The task of a production system is to provide a final or intermediate product for customers (NY Quist et al. Citation2008). Production systems have developed via Taylors, the Toyota Production System, and Lean Production in the twentieth century. Through Taylors, industrial work was transferred to economical mass production with methodical standardization and rationalization measures. Ford developed the automobile industry's first comprehensive production system for mass production (Taylor Citation1911; Path Citation2003; Borowski and Mile Citation2015). The Toyota Production System (TPS) is a holistic overall system of methods to shorten lead times, reduce costs, and increase quality. The TPS is founded on the elimination of waste and the continuous improvement process. The achievement of goals in TPS is made possible by the two pillars of Just in Time and Autonomous Automation (Jidda) (Ono Citation 1988; Borski and Mile Citation 2015). Lean Production, or Lean Manufacturing, has introduced methodical components of TPS to management practices of production systems and other business areas in the Western world (Womack and Jones Citation2003; Womack, Jones, and Room Citation1990; Liker Citation2021; Shah and Ward Citation2007; Borski and Mile Citation2015). Building upon the concept of? factory physics? by Hope and Spearman (Citation1996), Goreville and Antonio (Citation2006) propose the following definition for Lean Production:?Lean production is an integrated manufacturing system that is intended to maximize the capacity utilization and minimize the buffer inventories of a given operation by minimizing system variability (related to arrival rates, processing times, and process conformance to specifications).? (Goreville and Antonio Citation 2006).

2. Related works and terminology

In this section, relevant terminology and research contributions on the design of Lean Production Systems 4.0 (LPS 4.0) are presented. The abovementioned definition by VDI (Citation2012) serves as the central reference throughout this paper. Accordingly, Lean Production Systems not only encompass aspects of technical manufacturing processes but also organizational elements of planning and control of production processes in an overall company context. The general structure of Lean Production Systems is set up with a composition of the element's objectives, processes, principles, methods, and tools, while the content of these elements is company-specific. Figure 2 gives an overview of the five main levels, building the organizational structure of an LPS.

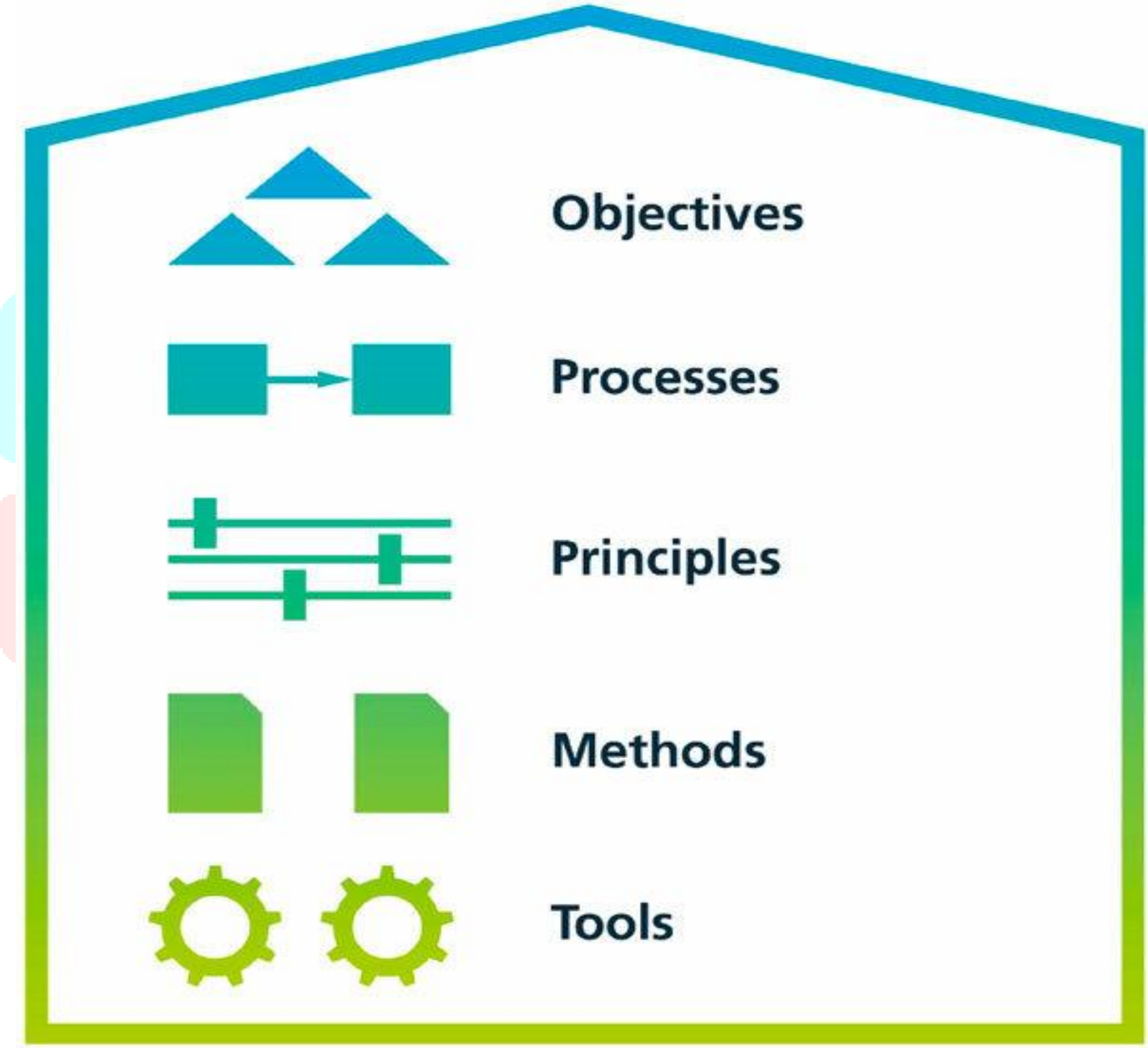

Figure 2. Organizational structure of Lean Production Systems.

LPS and Industries 4.0, pointing out the driving forces Industries 4.0 holds for the design of LPS. Based on this, Borowski and Richter (Citation2018) propose a conceptual framework for Lean Production Systems 4.0, in which data management plays an important role as an accompanying process and the set of methods and tools is expanded by digital solutions (cf. Borski et al. Citation2018). However, the details and practical application of the proposed framework remain unclear. By matching company-specific characteristics with a systematic method catalo and criteria, Borski et al. (Citation2021) present a selection methodology for methods and tools of Lean Production Systems 4.0. In continuation of the abovementioned research, Richter (Citation2021) developed a process model for the implementation of Industries 4.0 about Lean Production Systems, encompassing three modules. (1) assessment of processes and sociotechnical system, (2) configuration of process alternatives, and (3) introduction and implementation of measures. Building on

VDI (Citation2012), Richter (Citation2021) defines Lean Production Systems 4.0 as follows:?A Lean Production System 4.0 represents a synergetic approach based on LPS and Industries 4.0 to improve enterprise processes, which enables the implementation of Industries 4.0 based on an LPS to improve individual enterprise objectives. (Richter Citation2021). Recent scientific literature provides multiple valuable reviews and studies on the combination of Lean Production and Industries 4.0. Kohlberg and Rule (Citation2015) call for a suitable framework for the integration of Industries 4.0, respectively cyber-physical systems into Lean Production Systems. Their work was continued with research contributions to cyber-physical production systems (CPPS) in a lead project on smart LPS funded by the German Research Foundation (Anglo and Zurich Citation2021; Anglo, Simpler, and Zurich Citation2021; Simpler, Anglo, and Zurich Citation2020, Citation2019). Performing a systematic literature review on Lean Thinking and Industries 4.0, Bettencourt, Laves, and Lead (Citation2019) contribute a rather qualitative discussion of relevant articles. Another review is presented by Sony (Citation2018) with a qualitative discussion of mainly managerial implications.

3. Systematic literature review

A systematic literature review (SLR) is a conclusive, systematic, and reproducible method for the identification, assessment, and synthesis of existing research contributions (Fink Citation2010). The method focuses on a specific thematic domain, for which the reviewers need to examine the state of the research beforehand. The literature review itself is a process of secondary analysis of already existing research contributions (Terrace Citation 2016). Based on Fink (Citation2010), the methodological approach for this SLR is divided into six phases: (1) definition of a research hypothesis, (2) identification of relevant and appropriate databases, (3) postulation of suitable search terms per database, (4) definition of criteria for the screening process of searched results, (5) execution and documentation of the literature review by reviewers, (6) synthesis of the SLR results (Fink Citation2010).

With the relevant contributions on LPS 4.0 at hand, the next step in our research is a systematic literature review of the impact of the digital transformation on each level of LPS by measuring the number of contributions. This approach corresponds with the overall research questions and adds quantified observations from recent literature. More specifically, the aim is to characterize and analyse recent literature regarding the impact of Industry 4.0 on Lean Production System levels, following the definition of VDI (Citation2012). As Figure 2 shows, these system levels are (1) objectives, (2) enterprise processes, (3) principles, (4) methods, and (5) tools (VDI Citation 2012). The results of this SLR were recently published in Schumacher et al. (Citation 2021).

As an important detail for this SLR, it is inherent to LPS that the items of each level are interrelated with each other. While objectives, processes, and principles are distinctly delineated levels, the literature is rather inconsistent regarding methods and tools. Methods and tools can be related to one or more principles and serve as the operational measures for the realization of objectives. Both methods and tools can directly be linked with a principle (Schmidt Citation2011). Usually, one or several tools are used within a method to contribute to a principle. Hence, a logical separation into two levels of LPS is mostly common in literature. See Schumacher et al. (Citation2021b) for a detailed discussion of these interrelations. Figure 3 provides definitions for principles, methods, and tools, as well as an illustration of possible combinations of these elements.

Figure 3. Possible settings for the interrelation of methods and tools (Schmidt Citation2011).

4. Field study on Lean Production Systems 4.0

The scientific literature on the recent developments in the design of Lean Production Systems provides a set of hypotheses that can only be investigated by adding industrial practice to the analysis. Therefore, we conducted a field study surveying practical users from leading German manufacturing companies. This study puts the predominantly scientific-theoretical analyses into an application-oriented context with real problems from industry. A two-stage field study, comprising a quantitative survey using a web survey and a qualitative survey in the form of expert interviews was designed and conducted. Table 2 gives an overview of the methodical and temporal specifics for each study stage. The detailed study results have first been presented to German recipients by Schumacher et al. (Citation 2021a).

The findings of our field study are threefold. First, the results of the web survey with a large sample size of industrial practitioners help to evaluate scientific hypotheses. Second, detailed interviews with leading experts lead to insights on existing and upcoming design requirements and paradigms for LPS. Third, we present the synthesis of both study stages and conclude with guidelines for the design of Lean Production Systems 4.0 as the central result of the field study.

4.1 Research methodology and study design

The central research question of the field study is concerned with the identification of requirements for the design of Lean Production Systems 4.0. The research question encompasses the related work by various scientific contributions presented in Section 2 and was subdivided into seven hypotheses. The methodical operationalization of the hypotheses is a crucial scientific process for valid study results. For this, the study was designed with two analytical stages. The first stage was a quantitative analysis of 73 industrial practitioners from German manufacturing companies with a high knowledge of Lean Production and Industry 4.0. The anonymous participation in the iteratively pre-tested questionnaire was realized in the form of a web survey. Each hypothesis was subdivided into relevant questions according to good methodical practice, with a set of questions ensuring cross-checking for analytical purposes.

5. Statistical bias and reliability of Lean Production Systems 4.0

To assess statistical bias, survey results were tested for non-response bias and common method bias by Tortorella et al. (Citation2020c). For non-response bias, Mann? Whitney U test based on the nonparametric, *linker* scale items of the web survey was performed to compare differences between early and late responses (Armstrong and Overton Citation1977). At a significance level of??=? 5%, no significant differences (p? Lt; 0.05) in central tendency (median) were identified between early and late responses. To test for common method bias, Herman's single factor test was conducted. Although this test has several limitations, it is widely used in the scientific literature. The test results in a value of 18.25%, which indicates that common method bias is not likely to be a problem for the results of the web survey (Pods off et al. Citation2003; Aguirre-Turret and HU Citation2019).

4.3 Results

The results were carried out in the summer of 2020 with 75 participants. Due to the elimination of two blank entries, the net sample size is 73 participants. The non-random sampling process and sample size do not qualify for representative assumptions to be made for whole industries and other economies. However, the group of participants provides valuable insights into industrial practice, which have not been generated before. The questionnaire used in the web survey comprises 26 questions, with the first five questions surveying the personal and company-related data of the participants. Table 4 gives an overview of all 21 questions about the hypotheses. Asked about their knowledge concerning Lean and Industry 4.0, both categories were answered with ‘high’ or ‘very high’ by over two-thirds of the participants, stating the proficiency of the sample group.

Each of the 26 questions was statistically and graphically analyzed in detail. Most of the questions were operationalized by a five-level linker scale from ‘strongly disagree’ to ‘strongly agree,’ while hypothesis 2 was surveyed in a scenario selection and hypothesis 6 in a ranking. In addition to this, when asking for details about changing LPS elements, participants were facilitated with an option to submit individual textual inputs.

4.4 Results of the expert interviews

The expert interviews were used to add mainly qualitative detail to the analysis. In 18 interviews with leading practitioners from German manufacturing companies, the existing structures of LPS as well as the trends and resulting requirements for industrial engineering practice were studied. The first segment of the interviews gave a clear impression of the current state of LPS design in industrial practice. Most of the companies had already implemented and revised their company-specific LPS in the 1990s and 2000s. Many experts reported that the first attempts in solely copying the TPS elements were not sufficient and had to be reworked to meet company-specific requirements and cultural prerequisites. 12 out of 15 companies consider their LPS as fully implemented. When asked for LPS principles, methods, and tools in use, the experts named typical Lean elements from corresponding catalos such as VDI (Citation 2013).

4.5 Guidelines for the design of Lean Production Systems 4.0

As a synthesis of the insights provided by this study, we have developed 10 guidelines for the design of Lean Production Systems 4.0. These guidelines are based on the systematically identified requirements of industrial practice for the design of Lean Production Systems. Each guideline was validated by the data collected throughout the study and is related to a validated hypothesis as well as several codes from the analysis of the expert interviews. The formulation of design guidelines follows the five systematic guidelines for the methodologically correct creation of design guidelines, according to Reach et al.

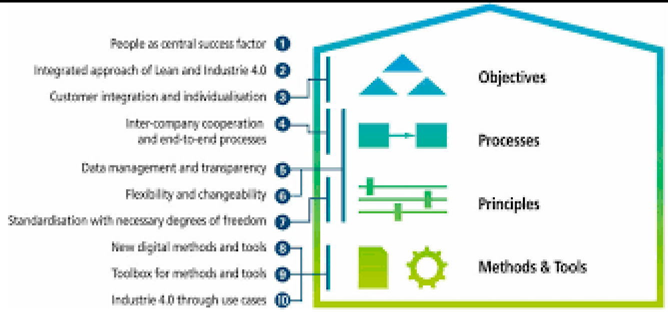

Figure:4 Guidelines for the design of Lean Production Systems 4.0 (Schumacher et al. Citation2021a).

4.6. Limitations of the field study

The presented field study is not free of limitations. First of all, the results of the study cannot simply be projected onto any international manufacturing company and economy. Statistically, the sampling process and sample size of the study do not allow for all universal conclusions, but the data proved to be reliable and free of biases. As a strength and weakness at the same time, the framework for our research is given by the German quasi-standard for Lean Production Systems, VDI (Citation2012), which is then combined with the mainly German-coined term Industry 4.0 and its related works. Even more, we have studied only German manufacturing companies. It is clear that this can have an impact on the results of our study and that the results cannot simply be transferred to other economies and domains. Solely English literature such as Bettencourt, Laves, and Leo (Citation2019) emphasize the importance of German literature in this field to be added to the international discussion. In return, we consider ourselves to be aware of relevant international research streams on Lean Production Systems 4.0, as well.

6. Discussion

In this section, the results of the analysis of academic literature as well as the field study are discussed about related other literature Section 5.1 and the initially stated three research questions in Section 5.2.

5.1 Discussion of related literature

About the systematic literature review from Section 2, other SLRs in the field of LPS 4.0 should be addressed. In an SLR on Lean Production in complex socio-technical systems, Silliman and Saurian (Citation2017) conclude that the contribution of Lean Production to manage complexity is a future research field that could be supported by a suitable implementation framework, as was also found in our study. Boer, Strand Hagen, and Chan (Citation2018b) performed an earlier and more insightful SLR with a lower number of contributions, giving insights into the strong link between Industry 4.0 and Lean Production. In Boer et al. (Citation2021), the complementary effect of Industry 4.0 and Lean is given evidence by correlating data of operational performance measures. As one of the results of bibliometric literature analysis, Ejsmont et al. (Citation2020) find various ‘Lean Industry 4.0 advantages’ based on Industry 4.0 technologies supporting Lean Production measuring factors. There are valuable recent approaches for the integration of digital measures from Industry 4.0 in Lean Production Systems such as Moue et al. (Citation2018), Mittal et al. (Citation2020) and Rosin et al. (Citation2020), supporting the approved hypotheses of our field study as well as the guidelines for LPS 4.0 design.

5.2 Discussion of research questions

In this section the contribution of our study to the research questions is reflected.

(1) Which Lean Production System levels are most influenced by the digital transformation according to academia (and practice)?

The digital transformation of LPS is a consensus in academia and practice (cf. Ciano et al. Citation2021; Boer et al. Citation2021; Kemble, Gunasegaram, and Done Citation2020). This research question is set up to identify differences with regard to the LPS levels, which has not been done before. When analysing, it is important to acknowledge that the assessment of the digital transformation on LPS levels is highly dependent on the professional qualification and background of the assessors as well as the research field of the journals analysed. Concerning these biases involved, the combined results of the presented analyses provide important insights. First, tools are attributed with the highest impact by Industry 4.0, especially through new technologies evolving.

(2) What are the requirements for the design of Lean Production Systems 4.0 by industrial practitioners?

The field study gives new and unique insights into the requirements of a large number of industrial practitioners for the design of LPS 4.0. As described in detail in Section 4.4, industrial engineers are facing increased complexity in the management of existing methods and new tools. A described solution could be the systematic development of a corresponding LPS 4.0 toolbox. Data management and analytics enhance the individually required skillset as well as the need for suitable infrastructure and corporate collaborative efforts.

(3) What are the guidelines for the design of future Lean Production Systems 4.0?

As a synergy of the theoretical background and the practical inputs by industry, 10 guidelines for the design of LPS 4.0 were developed in Section 4.5, answering this research question. Since guidelines are only recommendations for specific implementations, it is important to further operationalize these guidelines for practical use in the industry.

6. Conclusions

This paper addresses the highly dynamic applied research field of Lean Production Systems 4.0, especially their design by industrial engineers. For this, academia and industrial practice were analysed in a combined approach with a high amount of scientific literature analysed and a unique expert group of industrial practitioners surveyed. The systematic literature review of 62 out of 1600 scientific papers shows that especially the tools, processes, and methods in Lean Production Systems are subject to digital transformation. By involving industrial practice in a field study, quantitative and qualitative insights were used to identify requirements and guidelines for the design of future Lean Production Systems 4.0. The theoretical and practical contributions, as well as the limitations and future research, are presented in the following subsections.

6.1. Contributions to theory

Engineering research is concerned with the design of Lean Production Systems 4.0. Our paper adds valuable insights for academics. First, the SLR results provide researchers with a structured in-depth analysis of changes in LPS levels. In detail, 62 recent research contributions were analyzed and contextualized. Overall, the results show that tools and processes are highly influenced by Industry 4.0.

6.2. Contributions to practice

Except for single case studies mentioned in Section 2, we are not aware of any study on LPS 4.0 involving a high number of industry practitioners to evaluate research hypotheses in-depth. Hence, our study contributes with an original as well as an applied research approach. The threefold results of the web survey, expert interviews, and synthesis provide new and valuable insights for the design of LPS 4.0. In addition to empirical data, the field study provides practitioners with relevant qualitative details from their peer group. Important research fields derived from the field study are the focus on humans, data management, flexibility and changeability, and inter-company cooperation, which must be integrated into LPS 4.0 practice.

6.3. Limitations and future research

It is important to address the underlying limitations of the research methods and results presented in this paper. The systematic literature review is the most structured and methodical way of analysing academic contributions to a thematic field. However, the screening and analysis processes are both dependent on the individual decision making of the reviewers and it is always possible that valuable contributions are filtered out due to missing the requirements of a certain criterion. The field study is mainly limited with regard to statistical representation and a partially primed perspective from German and English engineering literature and German manufacturing companies analysed.

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