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Towards Digital Lean Cyber-Physical Production Systems: Industry 4.0 Technologies as Enablers of Leaner Production

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Abstract. Lean production emerged as an alternative way of organizing and managing manufacturing operations in the 1990s, following the close examination and promotion of the Toyota Production System as a better way of working. More recently, the advent of Industry 4.0 and its associated Cyber-Physical Production Systems has materialised novel ways of optimizing production operations. Though it is generally agreed that manufacturers should not neglect one of the aforementioned approaches in favour of the other, there remains uncertainty as to how Industry 4.0 technologies should be integrated with existing lean production programmes. This paper presents an overview of both approaches, and provides an exploratory study that examines the integration of Lean and Industry 4.0 in practice.

Keywords: Lean Production, Digital Lean Manufacturing, Cyber-Physical Production Systems, Industry 4.0.

1 Introduction

With the purpose of increasing operational performance and competitive advantage, many manufacturing firms have developed and deployed *lean production programmes* with the ultimate goal of creating a culture of continuous improvement [1] [2] [3]. Recent developments towards the Fourth Industrial Revolution, or Industry 4.0 [4], now encourage manufacturers to look at/into advanced technologies, automation and digitalization as the next digital frontier for improving the *lean enterprise* and achieving operational excellence.

Toyota Motor Co. is recognized as the pioneer of what has become widely known as *lean production* – with the company’s corporate philosophy: “The Toyota Way”, firmly underpinning its operations model, “The Toyota Production System (TPS)”. Sugimori et al. [5] was one of the first to describe the infamous TPS, describing it as two fundamental sub-systems: the Just-in-Time (JIT) system and Respect-for-Human (RFH) system. Furthermore, a description of the principles and behaviours underlying the “Toyota Way” philosophy can be found in Liker [6], who describes Toyota’s managerial approach as a set of 14 core “lean” principles. Some examples of these are “*use only reliable, thoroughly tested technology that serves your people and processes*”

and “*make decisions slowly by consensus, thoroughly considering all options*”. These specific examples support the notion that Toyota, as a company, is a slow adopter of new technology. However, one should by no means dismiss the new opportunities presented by emerging Industry 4.0 technologies [7] for further improvement and/or innovation of manufacturing operations. [8] to [13] present limited insight into the co-existence of both approaches, focusing on smart products, smart machines and augmented operators and cyber-physical JIT delivery respectively. This paper aims to offer a more holistic account of lean production and Industry 4.0 integration, presenting actual industrial Proofs-of-Concept (PoCs) from an explorative case study.

2 Literature Review

This paper addresses the co-existence and potential integration mechanisms of *Industry 4.0 technologies* [7] with existing industrial lean production programmes. This section provides an overview of relevant literature combining the fields of lean production and Industry 4.0 (see Table 1).

Table 1. Recent Literature Addressing Industry 4.0 and Lean Production Integration

Paper	Main Contribution
[8]	This research work explores the <u>co-existence</u> of lean production and Industry 4.0 in a smart network of machines, products, components, properties, individuals and ICT systems of a smart factory value chain.
[9]	This research work explores the Industry 4.0 offers as an estimated benefit for <u>stabilizing</u> lean processes with Industry 4.0 applications, and presents an Industry 4.0 impact matrix on lean production systems as a useable evaluation framework. The matrix considers elements of lean production systems with Industry 4.0 technologies and gives a first estimation of impact.
[10]	This research work conducts an analysis of <u>interdependencies</u> between the principles of lean production systems and Industry 4.0 based on the structuring of Industry 4.0 elements into technologies, systems and process-related characteristics of 260 use cases of applied Industry 4.0 technologies in the German industry.
[11]	This research work describes the <u>co-existence</u> of lean production and the implementation of Industry 4.0 technologies in a plot that it is drawn between drawbacks of lean and advantages of Industry 4.0.
[12]	This research work examines the <u>relationship</u> between lean production practices and the implementation of Industry 4.0 in Brazilian manufacturing companies based on a survey to 110 companies of different sizes and sectors, at different stages of lean production implementation. Findings indicate that lean production practices are positively associated with Industry 4.0 technologies and their concurrent implementation leads to larger performance improvements. Furthermore, the contextual variables investigated do matter to this association, although not all aspects matter to the same extent and effect.
[13]	This research work emphasizes the <u>interaction</u> between lean production and Industry 4.0 and proposes a methodology, which provides guidance for Industry 4.0 under lean production environment. Moreover, Industry 4.0 technologies and automation oriented lean production applications are also included.
[14]	This research work describes a practical approach to <u>interlink</u> the lean method world with the cyber-physical world. It combines the lean methodological approach with the Industry 4.0 technology-driven vision.

From literature, it is clear that *Lean Production* and *Industry 4.0* can be successfully integrated. In fact, it appears that the realization of lean principles can be further enhanced from the support offered by innovative digital technologies and cyber-physical systems, which are the major contributions introduced by Industry 4.0. Moreover, it is possible to consider the two approaches as complementary, because the strength of *lean manufacturing* that is based on participation and standardized practices can take advantage of the collaborative environment and structured data collection and analysis offered by Industrial Internet of Things (IIoT) and Cyber-Physical System (CPS) technologies. In order to better clarify the opportunities of combining lean production and Industry 4.0, we first provide a brief description of the technologies that are considered as the pillars of Industry 4.0 (see Table 2) [7] [15].

Table 2. Industry 4.0 Technologies: Commonly Accepted Definitions [7] [15]

Autonomous Robots	The evolution of traditional robots opened the way to new collaborative solutions of robots (i.e. CoBots) that are able to work together with humans in a safe and efficient way. Human-Robot Interaction (HRI) can enable high productivity [16]. Moreover, embedded intelligence in robots can allow them to learn from human activities, improving their autonomy and flexibility.
Simulation	Simulation tools can be widely used along all the value chain, starting from product design to operations management. Modelling and simulation tools are crucial for the development of digital engineering and virtual representation of products and processes, in order to identify in advance potential issues, avoiding cost and resource wastes in production [7].
Horizontal- and Vertical Integration	As defined in [17], horizontal integration refers to the creation of a global value network through the integration and the optimization of the flow of information and goods between company, suppliers and customers. The vertical integration, instead, is the integration of functions and departments of different hierarchical levels of the single company creating consistent flow of information and data.
Industrial Internet of Things	Industrial Internet of Things (IIoT) enables the communication among every device inside and outside the factory. [18] defines IIoT as a “non-deterministic and open-network in which auto organized intelligent entities and virtual objects will be interoperable and able to act independently pursuing their own objectives (or shared ones) dependently on the context, circumstances or environments”.
Cybersecurity	In order to guarantee the security of the large amount of data collected, stored and communicated via IIoT, cybersecurity strategies are one of the major challenges for the future [19].
Cloud Computing	Cloud computing is related to the ICT-infrastructure that allows the ubiquitous access to data from different devices. Cloud can be treated as a service and support collaborative design, distributed manufacturing, collecting innovation, data mining, semantic web-technology and virtualization [20].
Additive Manufacturing	Additive Manufacturing (AM) consists in a cluster of technologies that enable to produce small batches of products with a high degree of customization by adding rather than removing material from a solid block. The reduction of scrap material, a quicker market launch due to the rapid prototyping, a higher production flexibility and a lower number of required tools are the major advantages of this technology [21].
Augmented Reality	Augmented reality (AR) allows the creation of a virtual environment in which humans can interact with machines using devices able to recreate the workspace. Interesting applications of AR are related to the training of workers and the support in manual production activities [22].
Big Data Analytics	Big data is characterized by volume, variety and velocity (the 3Vs), and it requires new techniques of data processing and analysis [23]. Visualization, analysis and sharing of data are at the basis of analytics that support decision-making and improve self-awareness and self-maintenance of the machines.

3 Research Methodology

A single, exploratory case study approach is adopted, taking insight into the current *Industry 4.0 programme (i.e. Digital Transformation)* of an Italian producer of automotive parts and brake systems: Brembo S.p.A. – <http://www.brembo.com/en>.

A selection of ongoing Industry 4.0 initiatives and *Proof-of-Concept (PoC) pilots* were discussed with representatives of the company, including: Operations Director, Industry 4.0 Programme Manager, Continuous Improvement Manager, Shift Supervisors and Lean-Lab Coordinator.

By providing valuable insights from this explorative use case, this paper is able to highlight several ways in which Industry 4.0 technologies can be used to support and further develop a company’s existing lean production programme.

4 Exploratory Case Description

With approximately 9,000 employees distributed across 15 countries and 19 industrial production sites, the company achieved a turnover of €2.2 billion in 2016, following successive growth year-on-year in the previous ten years. Delivering OEM and after-sales parts and systems to the major automotive companies, and with an existing *lean production programme* (since 2008) and *lean production “office”* with eight *lean-labs* worldwide, the company demonstrates a clear understanding of its value propositions and major value streams.

The company established an Industry 4.0 committee and programme management team in 2015, and currently has more than 50 on-going Industry 4.0 initiatives, managed by “Digital Factory Project Managers” and executed by “Digital Factory Engineers”. The “Digital Personnel” works closely with personnel from the lean programme office to ensure the alignment of both initiatives. An example of this collaboration is the company’s lean-lab, which has recently been redesigned to cater for two core types of *lean-training*, the first for the more traditional human-intensive areas such as manual production and assembly operations, and the second for more Industry 4.0 relevant, capital-intensive areas like robotics and automation.

This investigation focuses on the company’s activities in the machining and assembly operations in the Italian factory, which has approximate 1,000 employees and produces in excess of 2,600,000 units per year. The factory has approximate 50 CNC machines and 50 assembly lines. We examine the company’s Industry 4.0 proofs-of-concept in machining, powder coating, and quality control operations, in addition to the company’s proof-of-concept for data management and e-learning. All four proofs-of-concept have been envisioned as strategic applications of Industry 4.0 technologies (see Table 3), and have been constructed as experiments implemented in the Brembo Factory located at Curno in Bergamo, Italy, in order to promote organizational learning. It is anticipated that the outcome and results of each PoC will be evaluated based on its contribution towards the company’s Profit and Loss (P&L) statement and strictly measured in terms of Return on Investment (ROI) before successful implementations are eventually rolled-out worldwide.

Table 3. Strategic Applications of Industry 4.0 Technologies at Brembo S.p.A.

Proof-of-Concept	Autonomous Robots	Simulation	Horizontal- and Vertical Integration	Industrial Internet of Things	Cybersecurity	Cloud Computing	Additive Manufacturing	Augmented Reality	Big Data Analytics
PoC A	•		•	•					•
PoC B	•		•	•					
PoC C			•	•					•
PoC D		•	•	•				•	•

4.1 PoC A: Machine Cell Automation and Smart Tool Management

Adoption of Industry 4.0 technologies [7] for automating machining and assembly operations shows extensive signs of promise for supporting both JIT and RFH systems. Applying a modular concept for machine cell automation based on standardisation and further machine improvement has resulted in improved performance in Quality, Cost, Delivery and Safety (QCDS) metrics. Robots are used for picking and visual inspection of raw metal-castings, as well as deburring. In-line quality inspection is also automated with use of integrated Coordinate Measuring Machines (CMMs), which has allowed 1/11 parts to be inspected instead of 1/100 without increasing the cycle time.

In the future, the company will realise autonomous set-ups – but today continue to work with the lean practice of Single Minute Exchange of Dies (SMED) for continuous

reduction of set-up time. All machine cells are also AGV-ready (Automated Guided Vehicle), suggesting a move towards unmanned logistics in the near future.

In addition to the efforts in machine cell automation, the company has also marked every tool with a unique identification, allowing for “Smart Tool Management”.

A database tracks the location and remaining lifecycle of each tool in real-time and generates a tool-wear forecast, allowing for more effective and efficient planning for tool replenishment in the tool preparation area. A production supervisor suggested, *“Operators in the tool preparation area are now able to prepare replenishment before the machine operator realizes the need”*.

The movement toward “Smart Tool Management” has resulted in at least 30% reduction in tool-inventory – and has an even greater effect with regard to tooling cost because of moving from fixed lifetime tool changes to condition-based tool-life.

4.2 PoC B: Powder Coating Automation

Following an analysis of the causes for poor quality in the powder coating department, the company realised that the masking and unmasking operations were responsible for generating a significant amount of defects. For this reason, the masking and unmasking operations have been fully automated using a high degree of innovation and robotics – resulting in significant cost savings and a swift return on investment. The process must manage 600,000 pieces per year, with a range of 15 colours and 30 different geometries, requiring 12 set-ups per day.

4.3 PoC C: Quality Control Digitization

The company has developed a “Smart Quality” concept, which involves the digitization of all dimensional quality control checks. This system also involves a 300-parameter in-line paperless CMM check. Before, there was a significant paper trail with regard to recording results of quality control, and the quality engineers/supervisors would have to physically search for documents from machine-to-machine. Now, the shift supervisor has a single access point (his/her PC) and receives a push warning via an on-line app on his smartphone should the pre-determined workflow render this necessary. This resulted in a paperless Quality Management System – with real-time Statistical Process Control (SPC), real-time process capability analysis, and real-time alerts in case of defect-detection.

4.4 PoC D: Data Management and e-Learning

The final proof-of-concept is the “Analytics Platform”, which connects all production lines on a common database and web-platform. A set of touch-screen dashboards situated directly in the shopfloor provides an instantaneous overview of the state of operations throughout the factory, in real-time. This allows for full real-time traceability per unit (including individual parameter information and test results), as well as web-analytics for shopfloor monitoring of both product and process. Because the information is collected and stored on a web-platform, workflows can be defined for various events, such as the detection of defects. For example, when a defective part is detected, automation in the production cell will remove the part from the line, and

the system can deploy a push-message to the shift supervisor’s smartphone. This system secures a fast flow of information to key stakeholders, offers broad visibility and provides a hierarchical escalation mechanism in the event of unplanned event detection. Most importantly in terms of the “Respect-for-Human” principle, the web-platform guides the production operator to act in the correct way.

The system also supports an *e-learning mechanism* for operator training. Digital instructions are provided across several levels – including safety, machine installation/ set-up procedures, machine maintenance procedures, and assembly procedures/work instructions. Each instruction is based on a 3D digital model of the machine, – and provides an animation that allows the operator to repeat the instruction in real life, acting as a self-assessment and test of understanding. This system was used to accelerate the opening and ramp-up of production in the company’s new factory in Mexico.

5 Findings and Discussion

Findings were organized according to the seminal work of Sugimori et al. [4], that describes TPS as the aggregation of two sub-systems: Just-in-Time (and Jidoka*) system and Respect-for Human System. These sub-systems are subsequently broken down into a sub-set of actions, as shown in Table 4. It is also suggested the enabling functionality of Industry 4.0 technologies for the various “lean production constructs” – on which the lean production programmes of many companies are based.

Table 4. Enabling Functionality of Industry 4.0 Technologies

Lean Production Constructs	Enabling Functionality of Industry 4.0 Technologies
<i>Just-in-Time (and Jidoka*) System</i>	
Reduction of cost through elimination of waste	Data analytics provides new and novel ways in which to plan and execute production and coordinate the upstream supply chain to support the Just-in-Time principle.
Withdrawal by subsequent processes	Enterprise-wide connectivity via a data analytics platform provides instantaneous real-time signalling for production and replenishment.
One piece production and conveyance	Shopfloor web-analytics tools provide suitable infrastructure for “track-and-trace” of one-piece-flow, providing real-time information and visibility of production operations. AGVs provide functionality for automatic conveyance of single units of work without the need for building physical conveyor lines.
Levelling of production	Through the adoption of smart automation technologies and big data analytics, <i>Heijunka</i> becomes much more realizable, allowing for greater optimization capabilities of planning and scheduling tasks, which are now supported by real-time monitoring of tasks execution. This enables minor adjustments to the schedule given unexpected or unforeseen events in production as well as turbulence in actual demand versus forecast.
Elimination of waste from overproducing	Data analytics platform provides real-time remote visibility of the status of operations, preventing and highlighting potential causes of waste such as overproduction.
Control of abnormality	In-line testing of products using automated coordinate measuring machines (CMMs) and subsequent digitalization of quality control documentation eliminates the burden of the previous, heavily manual quality assurance tasks. The intelligent automation of manual tasks that produce high-level of scrap and rework leads to significant cost savings.
<i>Respect-for-Human System</i>	
Full utilization of workers capabilities	The e-learning platform offers a digital environment (i.e. a virtual lab) for the operators training, which is combined with a physical laboratory for accelerating the upskilling and reskilling of operators.

* The term ‘Jidoka’ as used at Toyota means, “To make the equipment or operation stop whenever an abnormal or defective condition arises”.

Elimination of waste movement by workers	AGVs are supporting operators in reducing their unnecessary (non-added value) movements within the shopfloor.
Considerations to workers safety	The e-learning platform primary goal is to ensure that all operators and associates are well trained in safety procedures in their respective operations areas, not just on physical production and assembly procedures.
Self-display of workers' ability	The combination of the e-learning platform and the physical laboratory supports a competency-based training programme that allows assessing the operators and associates in his/her knowledge and skills, on applying such knowledge, for conducting different work instructions.

6 Conclusions and Further Research

This paper provides a review of lean production in light of emerging Industry 4.0 technologies. Specific reflections have been made regarding the potential of these technologies to build on existing lean production programmes and serve as enablers for leaner production. In particular, an exploratory case study of an Italian company operating in the automotive sector has been discussed in order to present some evidence from an actual implementation of Industry 4.0 proofs of concept. From the case study, the potential of digital technologies to support key lean manufacturing constructs emerged. This paper aimed at providing the foundations for further research, which can be towards a more detailed framework for “Digital Lean” or “Lean 4.0”.

In terms of limitations of the work, we recognize that from a single case study, it is difficult to make accurate theoretical generalisations of the topic(s) under exploration. Therefore, further case studies are required to verify the significance of the propositions presented in this paper. In addition, as the results presented in this paper cannot be considered exhaustive and fully extendible to all possible industrial realities, further development will include the enlargement of the sample considering different sectors in the B2B and B2C contexts, as well as extending the analysis to different tiers of the supply chain.

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References

1. Netland, T.H.: Exploring the Phenomenon of Company-specific Production Systems: One-Best-Way or Own-Best-Way? *Int'l. J. of Production Research*, 51:1084-1097 (2013)
2. Womack, J.P., Jones, D.T.: *Lean Thinking: Banish Waste and Create Wealth in your Corporation*. New York, Free Press (1996)
3. Netland, T.H., Powell, D.J.: *A Lean World*. In: Netland, T.H. and Powell, D.J. [Editors], *The Routledge Companion to Lean Management*. Routledge, New York (2017)
4. Thoben, K-D., Wiesner, S., Wuest, T.: “Industry 4.0” and Smart Manufacturing – A Review of Research Issues and Application Examples. *Int'l. J. of Automation Technology*, 11(1):4-16 (2017)

5. Sugimori, Y., Kusunoki, K., Cho, F., Uchikawa, S.: Toyota Production System and Kanban System – Materialization of Just-in-Time and Respect-for-Human System. *Int'l. J. of Production Research*, 15(6):553-564 (1997)
6. Liker, J.K.: *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. New York, McGraw-Hill (2004)
7. Sameer, M., Muztoba, K., Romero, D., Wuest, T.: Smart Manufacturing: Characteristics, Technologies and Enabling Factors. *Journal of Engineering Manufacture* (2017)
8. Mrugalska, B., Wyrwicka, M.K.: Towards Lean Production in Industry 4.0. *Procedia Engineering*, 182:466-473 (2017)
9. Wagner, T., Herrmann, C., Thiede, S.: Industry 4.0 Impacts on Lean Production Systems. *Procedia CIRP*, 63:125-131 (2017)
10. Dombrowski, U., Richter, T., Krenkel, P.: Interdependencies of Industrie 4.0 & Lean Production Systems: A Use Cases Analysis. *Procedia Manufacturing*, 11:1061-1068 (2017)
11. Karamveer, S.: Lean Production in the Era of Industry 4.0. *Logistics Engineering and Technologies Group - Working Paper Series 2017-005* (2017) Available at SSRN: <https://ssrn.com/abstract=3068847> or <http://dx.doi.org/10.2139/ssrn.3068847>
12. Tortorella, G.L., Fettermann, D.: Implementation of Industry 4.0 and Lean Production in Brazilian Manufacturing Companies. *Int'l. J. of Production Research*, DOI: 10.1080/00207543.2017.1391420 (2017)
13. Satoglu S., Ustundag A., Cevikkan E., Durmusoglu M.B.: Lean Production Systems for Industry 4.0. In: *Industry 4.0: Managing The Digital Transformation*. Springer Series in Advanced Manufacturing. Springer, Cham (2018)
14. Prinz, C., Kreggenfeld, N., Kuhlenkötter, B.: Lean Meets Industrie 4.0 – A Practical Approach to Interlink the Method World and Cyber-Physical World. *Procedia Manufacturing*, 23, 21-26 (2018)
15. Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., Harnisch, M.: Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. [online] Available: http://www.inovasyon.org/pdf/bcg.perspectives_Industry4.0_2015.pdf
16. Thoben, K. D., Wiesner, S., Wuest, T.: "Industrie 4.0" and Smart Manufacturing: A Review of Research Issues and Application Examples. *Int'l. J. of Automation Technology*, 11(1):4-19, DOI 10.20965/ijat.2017.p0004
17. Kagermann, H., Wahlster, W., Helbig, J.: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0 - Securing the Future of German Manufacturing Industry. Acatech, National Academy of Science and Engineering (2013)
18. Zuehlke, D.: Smart Factory: Towards a Factory-of-Things. *Annual Reviews in Control*, 34:129-138 (2010)
19. Khan, A., Turowski, K.: A Survey of Current Challenges in Manufacturing Industry and Preparation for Industry 4.0. In *Proceedings of the First International Scientific Conference "Intelligent Information Technologies for Industry" (IITI'16)*, pp. 15-26, Springer, Cham (2016)
20. Park, H.S.: From Automation to Autonomy - A New Trend for Smart Manufacturing. In: Katalinic, B., Tekic, Z. (Eds.), *DAAAM International Scientific Book* (2013)
21. Bhatia, U.: 3D Printing Technology. *Int'l. J. of Engineering Science*, 3:327-330 (2015)
22. Syberfeldt, A., Holm, M., Danielsson, O., Wang, L., Brewster, R. L.: Support Systems on the Industrial Shop-floors of the Future Operators' Perspective on Augmented Reality. *Procedia CIRP*, 44:108-113 (2016)
23. Kang, H.S., Lee, J.Y., Choi, S., Kim, H., Park, J.H., Son, J.Y., Do Noh, S.: Smart Manufacturing: Past Research, Present Findings, and Future Directions. *Int'l. J. of Precision Engineering and Manufacturing-GrePoen Technology*, 3(1):111-128 (2016)