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The link between Industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda

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Abstract: In recent years, Industry 4.0 has emerged as one of the most discussed concepts and has gained significant popularity in both academia and the industrial sector. Both Industry 4.0 and lean manufacturing utilise decentralised control and aim to increase productivity and flexibility. However, there have been few studies investigating the link between these two domains. This article explores this novel area and maps the current literature. This is achieved through a systematic literature review methodology, investigating literature published up to and including August 2017. This article identifies four main research streams concerning the link between Industry 4.0 and lean manufacturing, and a research agenda for future studies is proposed.

Keywords: Industry 4.0; smart manufacturing; lean manufacturing; cyber-physical systems; Internet of things; literature review

1. Introduction

Lean manufacturing is arguably the most prominent manufacturing paradigm of recent times (Womack, Jones, and Roos 1990; Holweg 2007). Lean manufacturing supports manufacturing companies in their efforts to improve in many areas, including reduced production cost, improved quality (Bhamu and Sangwan 2014), improved responsiveness by reducing lead times (Chauhan and Singh 2012), and increased flexibility (James-Moore and Gibbons 1997).

However, even if lean manufacturing has helped numerous companies reduce waste and thereby improve in several performance dimensions, many companies still struggle to successfully transform into a lean company (Jadhav, Mantha, and Rane 2014). Some companies fail to consider the strategic fit of lean practices, trying to implement it in environments where they

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are not applicable (Azadegan et al. 2013). Others might experience that the basic methods of lean manufacturing are not sufficient and hence do not meet the company's operational requirements (Kolberg and Zühlke 2015). Additionally, even if seemingly succeeding in their initial implementation phase, many companies find it difficult to sustain the initial momentum of their lean project (Netland 2016). To address these issues, it is relevant to investigate the solutions offered by information and communications technology (ICT).

Originating from the Toyota Production System, which can be traced back to the 1950s, lean manufacturing in its purest form is completely independent of any kind of ICT. However, the emergence of increasingly more advanced ICT solutions has increased the research effort into how lean manufacturing and ICT may cooperate to achieve better performance. Research into this area is summarised by, among others, Houy (2005), Ward and Zhou (2006), Riezebos, Klingenberg, and Hicks (2009), Powell (2013), and Maguire (2015). Evidence from industry also shows that companies are able to build hybrid solutions, where they are able to take advantage of both lean manufacturing and ICT solutions such as enterprise resource planning (ERP) systems (Riezebos, Klingenberg, and Hicks 2009) and manufacturing execution systems (MES) (Cottyn et al. 2011).

Despite numerous, recent studies investigating the interaction between ICT and lean manufacturing, few address the new possibilities introduced by Industry 4.0, also referred to as smart manufacturing (Kang et al. 2016). It has not been studied how an introduction of Industry 4.0 will influence already established management practices such as lean manufacturing and how already established lean practices will influence the implementation of Industry 4.0. Although having different approaches, Industry 4.0 and lean manufacturing share the same general objectives of increased productivity and flexibility (Frank 2014). The introduction of cyber-physical systems (CPS) and the Internet of things (IoT), key components of Industry 4.0, enable distributed computing and autonomy that is typically not found in traditional centralised ICT systems. This matches with traditional lean thinking, which favours decentralised structures with small modules and low levels of complexity (Thoben et al. 2014; Kaspar and Schneider 2015; Kolberg and Zühlke 2015) because complexity is enormously resource intensive (Kaspar and Schneider 2015).

The aim of the current article is to explore this novel area and present the current status of research regarding the link between Industry 4.0 and lean manufacturing. As a prerequisite for this, the key constructs are introduced and the postulated relationships between them are presented. Furthermore, the article identifies four research streams and presents key research findings in each area. Based on this, a research agenda for future studies is proposed.

The article is organised as follows: Section 2 introduces and defines the domain of Industry 4.0, while Section 3 outlines the connections between the main constructs and presents the conceptual framework that the current study is based on. Section 4 describes the research method, while the main findings from the literature review are presented in Section 5. In Section 6, the findings are discussed, and a research agenda is established, while Section 7 summarises and concludes the article.

2. The emergence of Industry 4.0

The pioneering proponents of the factory of the future found early on that inflexible and dedicated production lines should be exchanged with flexible machines and that computers will support this endeavour (Diebold 1952; Freeman 1988). The concept of ubiquitous computing was already envisioned more than 25 years ago by Mark Weiser (1991). Ubiquitous computing builds on the idea that computers are embedded throughout the environment, making them effectively invisible to the user (Weiser 1993). The rapid advances in ICT, exemplified by the introduction of technological solutions such as CPS and the IoT have ensured that this vision is coming closer to reality. The idea of an interconnected world has also gained attention from the industry sector, and the vision of a fourth industrial revolution is emerging, popularly known as Industry 4.0 (Kang et al. 2016). The increasingly affordable hardware and software solutions accelerate the transition towards the smart and interconnected factory envisioned by Industry 4.0 (Almada-Lobo 2016). With promises of manufacturing customised products at the same cost as mass production (Wang 2016), Industry 4.0 has gained significant popularity in both academia and in the industrial sector; companies worldwide are investing considerable sums into investigating how they can benefit from this emerging technology-based manufacturing paradigm.

Starting out as a German government programme to increase the competitiveness of their manufacturing industry (Kagermann et al. 2013), Industry 4.0 was announced at the Hannover Messe in 2011 (Drath and Horch 2014). It is a cooperation project between the private sector, academia and the government (Kang et al. 2016), and it revolves around *‘networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems’* (Kagermann et al. 2013, 20). However, with time, the term Industry 4.0 has evolved into an overall label for describing the next era of manufacturing, and in this process, it has become a poorly defined buzzword for the future of production. Even though Industry 4.0 is one of the most frequently discussed topics among practitioners and academics in the last few years, no clear definition of the concept has been established; therefore, no generally accepted understanding of Industry 4.0 has yet been published (Brettel et al. 2014; Hermann, Pentek, and Otto 2016; Rüttimann and Stöckli 2016; Hofmann and Rüsçh 2017). Researchers and practitioners have different opinions regarding which elements compose Industry 4.0, how these elements relate to each other and where Industry 4.0 is applicable. Surveys show that few practitioners are able to provide a concrete definition of Industry 4.0 (Heng 2014). Some even claim that Industry 4.0 does not bring something new, that it merely combines existing technologies and concepts into a new package with a catchy marketing name (Drath and Horch 2014). This ambiguity and lack of a clear definition will lead to communication difficulties and complicate research and education on the subject (Pettersen 2009), as well as make it more difficult for companies to identify and implement Industry 4.0 solutions (Hermann, Pentek, and Otto 2016).

Recent studies have found more than 100 different definitions of Industry 4.0 (Moeuf et al. 2017). Thus, it is important to clarify the definition used to ensure construct validity. In the current study, Industry 4.0 is operationalised as *the usage of intelligent products and processes, which enables autonomous data collection and analysis as well as interaction between products, processes, suppliers, and customers through the internet*. Similar to Liao et al. (2017), the relevant literature must be related to CPS, IoT, smart factories, or digitalisation.

3. Linking Industry 4.0 and lean manufacturing

The main point of interest for this article is to investigate the link between Industry 4.0 and lean manufacturing, as well as examine its implications on performance and the environmental factors influencing these relationships. Therefore, the first step is to develop a conceptual framework that explains the main constructs and the relationships between them.

Ohno (1988) describes the two pillars needed to support the Toyota Production System: just-in-time (JIT) and autonomation (jidoka). These pillars are also found in lean manufacturing (Bicheno and Holweg 2009). To successfully implement JIT, accurate and timely information sharing is a prerequisite (Haynes, Helms, and Boothe 1991; Zelbst et al. 2014). Accurate inventory data are especially important in lean supply chains because large buffers and safety stocks are eliminated. A digitalised supply chain will support this by providing timely and accurate data about inventory levels and location (Zelbst et al. 2014). Autonomation is about giving intelligence to the machines so that they autonomously can distinguish between normal and abnormal operations. Therefore, machines will stop if there is a problem, so no defective products are produced (Ohno 1988). The implementation of CPS in production gives machines intelligence and thereby facilitates autonomation. The machines will be able to report deviations faster, analyse the causes, and initiate measures automatically (Thoben et al. 2014).

Roy, Mittag, and Baumeister (2015) argue that the introduction of Industry 4.0 does not eliminate lean manufacturing but rather helps to increase the maturity of the firm's lean programme. Rüttimann and Stöckli (2016) predict that Industry 4.0 will materialise in pieces that have to be integrated into existing lean frameworks and will eventually increase the flexibility of lean manufacturing. The term *lean automation* slowly gained popularity throughout the 1990s, and it concerns developing automation solutions with a low level of complexity that fits lean production environments (Jackson et al. 2011). The new possibilities enabled by Industry 4.0 have reignited some of the research within this field (Kolberg and Zühlke 2015; Kolberg, Knobloch, and Zühlke 2017).

Lean manufacturing focuses on eliminating all kinds of waste in the production process by identifying any unnecessary activities, streamlining the process, and creating standardised routines. Simple machines and workstations with low levels of complexity facilitate automation and digitalisation of the manufacturing process (Kolberg and Zühlke 2015). Lean manufacturing also emphasises visual control and transparency, which makes it easier to identify problems in the process. This has led to some researchers claiming that a lean implementation necessarily must be seen as a prerequisite for a successful Industry 4.0

transformation (Kaspar and Schneider 2015; Staufen AG 2016). Based on a survey of 179 industrial companies, Staufen AG (2016) find that the similarity between the Industry 4.0 pioneers is that they have already implemented a lean manufacturing system, which may show lean is an ideal foundation when shifting towards Industry 4.0. Khanchanapong et al. (2014) similarly suggest that advanced manufacturing technologies (AMTs) may need to be supported by lean practices to maximise the manufacturing performance increase.

The performance benefits of implementing lean manufacturing are proven in numerous cases and concern a broad range of different performance metrics. Marodin and Saurin (2013) classify the performance benefits of implementing lean manufacturing into five groups: (1) operational, (2) financial, (3) human, (4) market, and (5) environmental. Duque and Cadavid (2007) further define how specific lean practices are affecting different operational performance metrics. From cases reported in the literature, Moeuf et al. (2017) investigate the observed performance benefits of implementing Industry 4.0; they find that increased flexibility is the most common reported performance benefit, followed by improved productivity, reduced cost, reduced delivery time, and improved quality. Regarding the performance impacts of combining lean manufacturing with AMTs, Khanchanapong et al. (2014) find that the synergistic performance impact of such an integration motivates the joint optimisation of the two rather than optimising either resource alone.

The contingency theory states that organisations have to adapt their structures to fit with their environment to achieve high performance (Donaldson 2001; Sousa and Voss 2008). To distinguish among different environments, internal and external environmental factors that can influence the organisation should be mapped. Thus, an environmental factor is defined as *an identifiable element in the environment that influences the organisation's operations*.

In addition to the moderating effect on performance, environmental factors tend to influence the applicability and implementation approach of improvement programmes (Netland 2016). Lean manufacturing emerged from the automotive industry and has successfully been adopted by other repetitive production environments. However, the extent to which lean principles are suitable for non-repetitive environments has been questioned (Cooney 2002). The lean practices and methods developed for mass production do not usually fit these environments (Horbal, Kagan, and Koch 2008; Matt 2014), which tend to experience major difficulties when seeking to implement lean practices (Portioli-Staudacher and Tantardini 2012). Similarly, for Industry 4.0, it is argued that environmental factors will have a significant impact on the applicability of Industry 4.0. Through a multiple case study, Strandhagen et al. (2017) find that companies with repetitive production systems on a general basis should have an easier transition to Industry 4.0 than non-repetitive production systems. Other researchers claim that only big enterprises will be able to reap the benefits from Industry 4.0 and that small and medium-sized enterprises (SMEs) can quickly become the victims of Industry 4.0 (Sommer 2015). Smaller enterprises will suffer because of the high investments needed, and the increased flexibility introduced by Industry 4.0 will allow bigger enterprises to steal market shares for customised products, a market segment now usually dominated by SMEs (Rüttimann and Stöckli 2016).

From the literature presented above, Figure 1 illustrates the different theoretical lenses regarding the relationships between Industry 4.0, lean manufacturing, performance, and environmental factors. The purpose of the conceptual framework in Figure 1 is to establish a structure for summarising the literature findings presented in Section 5. The four relationships in the framework are described as follows:

- (a) Industry 4.0 technologies can support and further develop well-known lean manufacturing practices, that is, *Industry 4.0 supports lean manufacturing*.
- (b) Established lean manufacturing systems exert facilitating effects on Industry 4.0 implementations, that is, *lean manufacturing supports Industry 4.0*.
- (c) The changes imposed on the production system by the integration of Industry 4.0 and lean manufacturing affects different performance dimensions of the system, that is, it illustrates the *performance implications of an Industry 4.0 and lean manufacturing integration*.
- (d) Based on similar studies, it is likely that environmental factors influence the potential to integrate Industry 4.0 and lean manufacturing, as well as the resulting performance of such an integration, that is, it depicts *the effect of environmental factors on an Industry 4.0 and lean manufacturing integration*.

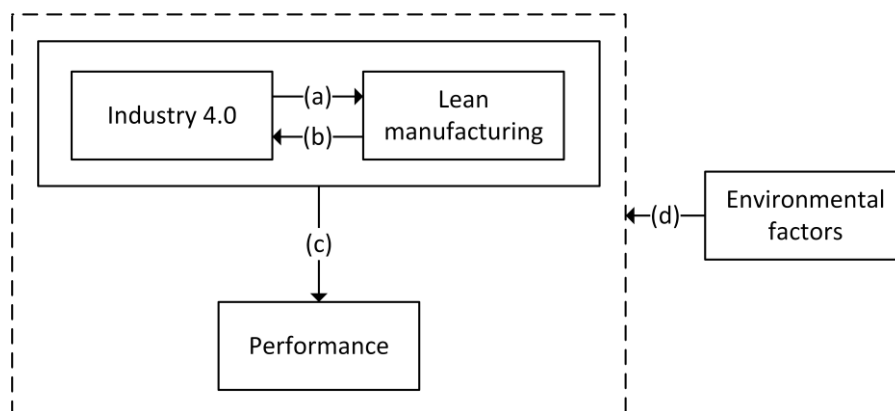


Figure 1: Conceptual framework illustrating the relationships between Industry 4.0, lean manufacturing, performance and environmental factors

4. Research method

This literature review is based on a systematic literature review approach, which ensures replicability by using transparent steps. A systematic review establishes a firm foundation for future research and facilitates theory development, aligns existing research, and uncovers areas where additional research is needed (Webster and Watson 2002).

Based on the extensive literature review by Liao et al. (2017), search terms connected to Industry 4.0 were selected. Liao et al. (2017) present a list of phrases that are the most related

to and commonly used together with Industry 4.0. Based on these keywords and the operational definition presented in Section 2, a comprehensive list of Industry 4.0 search terms was established (Appendix 1). Lean manufacturing is a considerably more established domain than Industry 4.0, and we therefore assumed that it is sufficient to use the two search terms ‘lean manufacturing’ and ‘lean production’.

The literature searches were conducted through the academic databases Scopus, ProQuest, Web of Science, ScienceDirect, and EBSCO. Table 1 presents the number of search results in each database. Scopus by far returned the most results, while ScienceDirect and EBSCO returned the fewest.

Table 1: Search results in each of the databases.

	Scopus	ProQuest	Web of Science	ScienceDirect	EBSCO
Results	57	18	17	8	7

An important part of any systematic literature review is to establish inclusion and exclusion criteria (Meline 2006). This ensures an objective reasoning behind the choice of literature. The inclusion criteria, guiding the choice of databases and filtering settings in the database, are as follows: only peer-reviewed academic *journal articles*, *conference articles*, or *book sections* available up to and including August 2017 were considered. After obtaining the initial set of articles from the different databases, the first step was to remove duplicates. Table 2 illustrates the duplication between the five databases used. EBSCO and Scopus had the highest duplication percentage, where 85.7% of the articles found in EBSCO also could be found in Scopus. On the other hand, ScienceDirect had no duplicate results with neither ProQuest nor EBSCO.

Table 2: Duplication of search results among the databases.

	Scopus	ProQuest	Web of Science	ScienceDirect	EBSCO
Scopus	-	-	-	-	-
ProQuest	5	-	-	-	-
Web of Science	12	4	-	-	-
ScienceDirect	5	0	4	-	-
EBSCO	6	4	5	0	-

Next, the first screening process investigated the titles and abstracts of the identified articles and excluded articles that were: (1) not in English, (2) not a peer-reviewed academic article, (3) not related to Industry 4.0 and lean manufacturing, or (4) without a full text published online. For the remaining articles, full-text articles were collected and screened. Articles were excluded in this second screening process if they were considered only vaguely related to this topic. The typical examples of articles excluded because of this criterion are articles that mention Industry

4.0 and/or lean manufacturing as examples without further analysis between the two. The inclusion and exclusion criteria are summarised in Table 3. The remaining articles at this stage were included in the literature analysis.

Table 3: Inclusion and exclusion criteria.

Inclusion criteria	<ul style="list-style-type: none"> • Document type: <i>Journal article, conference article or book section</i>
Exclusion criteria	<ul style="list-style-type: none"> • Non-English (NE) • Not peer-reviewed academic literature (NP) • Not related to Industry 4.0 and lean manufacturing (NR) • No full text (NF) • Vaguely related to Industry 4.0 and lean manufacturing (VR)

Based on this methodology, the initial sample of 107 articles was reduced to 21 articles for the literature analysis. As shown in Figure 2, the process of filtering articles is depicted according to the PRISMA flowchart. Out of the 21 articles included in the analysis, 18 of these could be found in the Scopus database. This indicates that Scopus is the most relevant academic database for finding articles relating to the integration of Industry 4.0 and lean manufacturing.

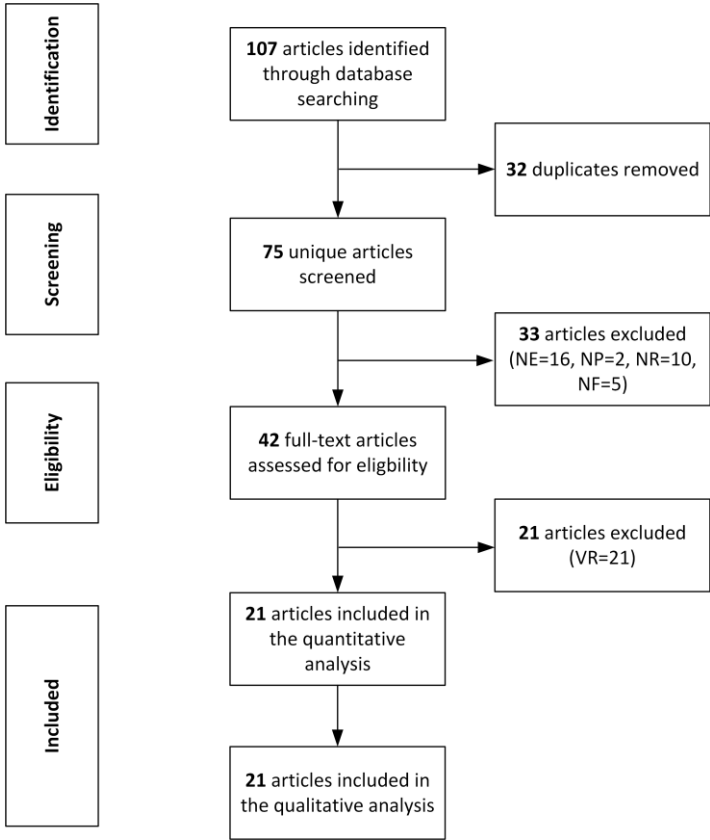


Figure 2: The PRISMA flowchart illustrates the different phases in the systematic literature review (Adapted from Moher et al. (2009)). See Table 3 for explanations of the exclusion codes.

The relevant articles were collected in a database where they were sorted, categorised and had their main theoretical standpoint and findings extracted. The software used for this was EndNote X7 for reference management and NVivo 11 for coding the literature.

5. Presentation of the current literature on the link between Industry 4.0 and lean manufacturing

The review identified 21 articles that comply with the inclusion and exclusion criteria and thus present a contribution towards explaining the link between Industry 4.0 and lean manufacturing. This section will first give an overview of the articles included in the analysis before classifying them according to the conceptual framework presented in Section 3. The most important findings are then presented according to the proposed classification scheme.

5.1 An overview of the included literature

Table 4 presents both the number of articles published per year as well as the research methods utilised. It is clear that this is an emerging research area, with most of the studies being published in 2016 and 2017. Out of the 21 articles in the final sample, 11 of the articles are conference articles while 10 are journal articles. Germany is the biggest contributor, with six of the articles originating from German universities or research institutions.

Table 4: Research methods in the investigated articles.

	Action research	Case study	Experimental	Mixed methods	Conceptual	Literature review	Total
2014	1	-	1	-	-	-	2
2015	-	-	-	1	1	-	2
2016	2	1	-	2	3	1	9
(2017)	1	1	1	2	2	1	8
Total	4	2	2	5	6	2	-

5.2 Key findings and literature classifications

By using the proposed conceptual framework to categorise the articles, it is easy to identify the main theoretical perspective of the article and the areas it investigates. Because the current study investigates the links between established constructs rather than the constructs themselves, the articles are categorised according to the four arrows describing the relationships, where each arrow represents a subsection in the review. Figure 3 presents the classification of the articles.

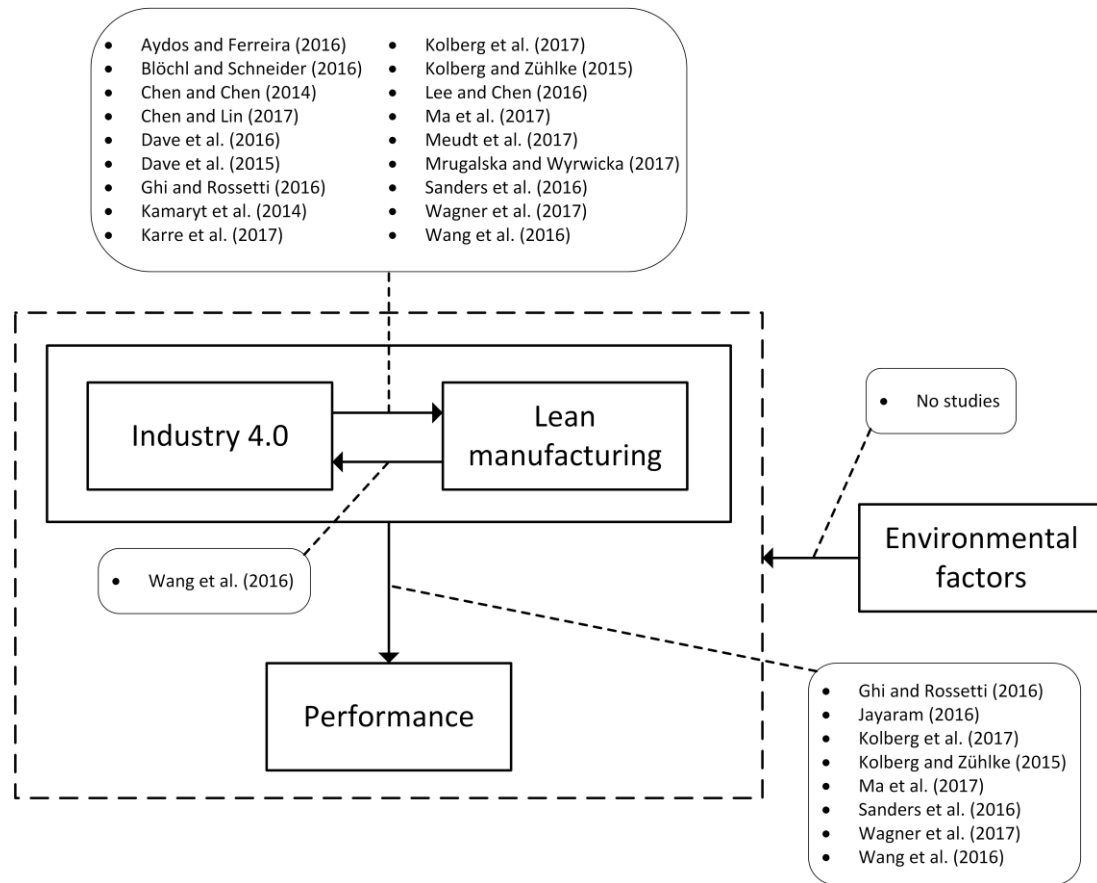


Figure 3: Categorisation of the articles according to the proposed conceptual framework

5.2.1 Industry 4.0 supports lean manufacturing

This section reviews the existing literature that discusses how Industry 4.0 can support lean manufacturing, both in the implementation phase and for established lean systems.

Sanders, Elangeswaran, and Wulfsberg (2016) investigate the different dimensions of lean manufacturing and how Industry 4.0 solutions might help overcome lean implementation barriers. They list 23 different lean implementation barriers and propose viable solutions from the Industry 4.0 domain. Value stream mapping (VSM) is a fundamental lean tool and often seen as a starting point in a lean implementation process. It is used to map the current process and identify improvement areas in the value stream. Traditional VSM is a manual ‘pen-and-paper’ process, and the data collection for it can often be challenging and tedious. In addition, it only offers a ‘snapshot’ of the process, and small changes could change this picture dramatically. Industry 4.0 can enhance VSM through the real-time collection of data (Chen and Chen 2014; Meudt, Metternich, and Abele 2017; Mrugalska and Wyrwicka 2017). Meudt, Metternich, and Abele (2017) introduce the concept of ‘Value stream mapping 4.0’. Their method mainly focuses on information logistics and is a tool for detecting wastes in the information flows within a company. Chen and Chen (2014) propose a real-time VSM system that can assist companies in their lean implementation by automatically creating value stream maps. By automating data collection, both the time spent on collecting data and the probability

of error are reduced. In addition, a dynamic picture of the shop floor is created, which increases the information visibility and supplies the decision makers with accurate and real-time information (Chen and Chen 2014). This kind of real-time VSM offers excellent possibilities for waste reduction, as well as immediate feedback on decisions. This facilitates experiments in production, for instance, related to batch sizes and production sequencing.

Companies that have already implemented lean manufacturing need guidelines on how to react to the impacts of Industry 4.0 (Meudt, Metternich, and Abele 2017). These companies need to integrate the new technologies from Industry 4.0 into their existing lean manufacturing systems (Wagner, Herrmann, and Thiede 2017), but the knowledge of how this should be done is still immature (Kolberg and Zühlke 2015; Wagner, Herrmann, and Thiede 2017). It is unclear which practices could be combined, which ones complement each other and which contradict each other. Among others, this knowledge will be important in the endeavour to tailor company-specific production systems.

Blöchl and Schneider (2016) claim that processes designed according to lean principles can be further optimised to deal with higher complexity by using Industry 4.0 technology. Similarly, Wang et al. (2016) claim that smart manufacturing can help companies achieve a higher level of lean, and investigate the impact on lean manufacturing from technologies related to data collection, big data analysis, and integrated processes. Wagner, Herrmann, and Thiede (2017) investigate what impact Industry 4.0 will have on existing lean practices. Together with Industry 4.0 and lean manufacturing practitioners, they develop an impact matrix that can be used as a decision support tool on how to integrate these emerging technologies into existing lean systems. Karre et al. (2017) describe the planned transition of a lean learning factory towards an Industry 4.0 state. In the article, they present numerous ideas on how lean practices can be enhanced using Industry 4.0 technologies. Ma, Wang, and Zhao (2017) claim that the emergence of Industry 4.0 has widened the application range of Jidoka and presents a smart Jidoka system based on CPS technologies. Chen and Lin (2017) argue how 3D printing can facilitate some objectives of lean manufacturing, such as one piece flow and JIT deliveries.

The analysed articles present several scenarios on how Industry 4.0 can enhance traditional lean manufacturing practices. Table 5 summarises these findings by illustrating which studies discuss the impact of Industry 4.0 on which lean practices. The lean practices presented have been cross-referenced with the review by Pettersen (2009) to ensure that they are inside the lean manufacturing domain. Table 5 further differentiates between ‘hard’ and ‘soft’ lean practices. ‘Hard’ refers to the technical and analytical practices used in lean, while ‘soft’ concern people and relations (Bortolotti, Boscarì, and Danese 2015). This categorisation will be discussed further in Section 6.

Table 5: Studies investigating Industry 4.0 impacts on specific lean practices.

	Lean practice	Chen and Chen (2014)	Chen and Lin (2017)	Karre et al. (2017)	Kolberg, Knobloch, and Zühlke (2017)	Kolberg and Zühlke (2015)	Ma, Wang, and Zhao (2017)	Meudt, Metternich, and Abele (2017)	Mrugaliska and Wyrwicka (2017)	Sanders, Elangeswaran, and Wulfsberg (2016)	Wagner, Herrmann, and Thiede (2017)	Wang et al. (2016)
'Hard' lean practices	Andon				X	X	X		X	X	X	
	Heijunka				X						X	
	Just-in-time deliveries				X	X						
	Kanban		X		X	X		X	X	X	X	X
	Man-machine separation										X	
	One piece flow		X	X							X	X
	Poka Yoke					X			X			
	Single-minute exchange of die			X		X			X	X		
	Standardized work										X	
	Statistical process control			X	X	X				X		
	Takt production										X	
	Total productive maintenance			X								
	Value stream mapping	X						X	X			
	Waste reduction										X	
'Soft' lean practices	5S		X								X	
	Kaizen								X		X	
	People and teamwork										X	

5.2.2 Lean manufacturing supports Industry 4.0

Another perspective on the interaction between Industry 4.0 and lean manufacturing is that lean manufacturing can be used as a foundation to build an Industry 4.0 implementation on. The streamlined and waste-free process obtained through a lean transformation simplifies further efforts to automate and digitalise the manufacturing process.

Wang et al. (2016) argue that a production process that already has implemented lean manufacturing is more likely to be modelled and controlled. Therefore, they argue that this

environment is an easier foundation for building a smart manufacturing platform on.

5.2.3 Performance implications of an Industry 4.0 and lean manufacturing integration

A key area of interest for most improvement programmes is their effect on performance. Some authors conceptualise the possible performance benefits of an Industry 4.0 and lean manufacturing integration. Others have empirical evidence based on experimental demonstrators, case studies, or action research in actual production environments.

Sanders, Elangeswaran, and Wulfsberg (2016) argue how Industry 4.0 together with lean manufacturing can improve productivity, reduce waste and consequently reduce costs. Kolberg and Zühlke (2015) describe how modular workstations and flexible manufacturing lines working together with single-minute exchange of die can reduce the set-up time. They also argue for how autonomous Kanban bins that can detect their inventory level and automatically order parts from suppliers can help reduce inventory levels. Ma, Wang, and Zhao (2017) show how CPS-based smart Jidoka is a cost-efficient and effective approach to improve production system flexibility. They also prove other benefits such as increased reliability and reduced cost. Table 6 illustrates the identified performance benefits reported in the investigated articles. However, the studies have only focused on operational performance metrics.

Table 6: Studies evaluating the performance benefits of integrating Industry 4.0 and lean manufacturing.

Performance dimension	Conceptual research			Empirical research				
	Ghi and Rossetti (2016)	Jayaram (2016)	Sanders, Elangeswaran, and Wulfsberg	Kolberg, Knobloch, and Zühlke (2017)	Kolberg and Zühlke (2015)	Ma, Wang, and Zhao (2017)	Wagner, Herrmann, and Thiede (2017)	Wang et al. (2016)
Cost			X			X		
Flexibility			X	X	X	X		X
Productivity			X					X
Quality	X	X						
Reduced inventory				X	X		X	
Reliability						X	X	

5.2.4 The effect of environmental factors on an Industry 4.0 and lean manufacturing integration

The literature review uncovered no articles studying the effect of environmental factors on an Industry 4.0 and lean manufacturing integration *per se*. However, some knowledge can be gathered by investigating in which sectors the studies were conducted. Although this will not give any information regarding in which sectors an Industry 4.0 and lean manufacturing integration is *not* beneficial, it will give some hints regarding which sectors research has already

been carried out in. Table 7 presents an overview of the relevant studies, showing that with the exception of the study from the construction industry, most studies are from typical repetitive production environments.

Table 7: Overview of the studies on integrating Industry 4.0 and lean manufacturing in different sectors.

Sector	Aydos and Ferreira (2016)	Chen and Chen (2014)	Dave et al. (2016)	Ma, Wang, and Zhao (2017)	Wagner, Herrmann, and Thiede (2017)
Automotive				X	X
Construction			X		
Forging	X				
Machining	X				
Parts manufacturing		X			

6. Pointing out future research directions

The current article has reviewed the existing literature regarding the link between Industry 4.0 and lean manufacturing. It is clear that this is a growing research area, reflecting the current trend in the industrial sector. This section discusses the findings from the literature review and points out a research agenda based on the identified gaps in the literature.

The literature review only identified 21 relevant academic articles, which is surprising because of the popularity of these two domains in recent years. Given the sizeable proportion of companies that currently have implemented some form of lean manufacturing, this calls for more research to ensure that companies can base their future improvement projects on a solid theoretical foundation.

The proposed agenda for future research is based on what the current body of literature insufficiently addresses or answers. Future research should focus on filling in these evident gaps in the literature. Research gaps in the following five areas have been pointed out:

1. The impact of Industry 4.0 on ‘soft’ lean practices
2. The facilitating effects of lean manufacturing on Industry 4.0 implementations
3. Empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration
4. The effect of environmental factors on the integration of Industry 4.0 and lean manufacturing
5. Implementation framework for moving towards an Industry 4.0 and lean manufacturing integration

6.1 The impact of Industry 4.0 on ‘soft’ lean practices

As seen in Table 5, most of the studies investigate how Industry 4.0 can enhance the ‘hard’ practices of lean. There have been few studies investigating how the introduction of Industry 4.0 will impact the shop floor initiatives typically associated with lean, such as continuous improvement efforts (Kaizen), teamwork, workforce involvement and autonomy, and 5S. Although sometimes overlooked, these so-called soft practices are crucial not only for achieving high performance through lean manufacturing, but also for sustaining performance in the long term (Bortolotti, Boscari, and Danese 2015).

It is known that improvement projects tend to fail if workers start feeling that their jobs are threatened (Womack 1996). It is therefore important for companies to ensure employees that no one will be laid off, but that the company rather will be seeking new market opportunities. If not, the organisation might end up with a situation that resembles a *continuous improvement paradox*, in which employees, through optimising the process, make themselves redundant. The increased automation levels also change the shop floor landscape, leading to a decrease in standardised low-skill work and an increase in high-skill activities. This means that continuous learning, training, and education of the workforce will be essential to adapt to the qualification requirements resulting from Industry 4.0 (Bonekamp and Sure 2015).

There is evidence that involving employees in Kaizen events positively affects their job satisfaction (Smith 2003). Other stated benefits of continuous improvement efforts include increased employee commitment, improved performance, quality, and customer satisfaction, together with reduced waste and costs (Fryer, Antony, and Douglas 2007). The increased process complexity will indeed influence the possibilities for shop floor personnel to involve themselves in improvement projects. A central question is consequently how the increase in process complexity following an Industry 4.0 transformation will affect the usage of ‘soft’ lean practices and, in turn, how this impacts both the job satisfaction and operational performance.

6.2 The facilitating effects of lean manufacturing on Industry 4.0 implementations

‘The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency’. – Bill Gates (cited in Krishnan (2013))

This quote illustrates why lean thinking is still important in an increasingly automated and digitalised world. It highlights the inevitable fact that an inefficient process that is automated is still inefficient (Nicoletti 2013) and is basically automating some type of waste. The cost of automating an inefficient process also tends to be higher (Kaspar and Schneider 2015).

Although the literature gives some indications on the facilitating effects of implementing lean prior to an Industry 4.0 transformation, no study has investigated this topic in-depth. The existing studies typically handle this question at a high level, without investigating whether there are specific parts of lean that are causing this effect. An interesting aspect would be to investigate whether the ‘hard’ aspects of lean, such as the organisation of production resources,

are the most important ones for this effect or whether it is the ‘soft’ aspects of lean. Future studies should investigate the reasons behind this phenomenon and how it affects implementation frameworks for Industry 4.0.

6.3 Empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration

Table 6 presents the current studies discussing the performance impacts of combining Industry 4.0 and lean manufacturing. However, several of these studies only discuss and hypothesise on a conceptual level, while some of the empirical studies collect their data from secondary sources. To motivate an Industry 4.0 and lean manufacturing integration, it is necessary to further investigate the potential performance implications through empirical studies. Although the current sample of studies gives some indications on the potential performance impacts, the studies are clearly insufficient in both width and depth. Central research issues in the future will be to measure what a successful Industry 4.0 and lean manufacturing integration entails, as well as comparing the performance impacts with those of a ‘pure’ Industry 4.0 or lean manufacturing system.

6.4 The effect of environmental factors on the integration of Industry 4.0 and lean manufacturing

As discussed in Section 3, it is likely that environmental factors will affect both the potential to integrate Industry 4.0 and lean manufacturing, as well as the resulting performance of the integration. The literature review found no studies that neither confirmed nor denied this hypothesis, still leaving this as a research gap. The sector analysis in Table 7 shows that most of the current studies have been conducted in repetitive production environments, which is similar to where both Industry 4.0 and lean manufacturing separately have been deemed most applicable by earlier studies.

Future research should focus on how environmental factors both affect the performance and compatibility of the two domains. These are critical issues to investigate in the endeavour to identify which environments might reap the largest benefits of an Industry 4.0 and lean manufacturing integration. An example of a promising research area is whether Industry 4.0 can assist in making lean manufacturing applicable in environments where it previously has been deemed unsuitable.

6.5 Implementation framework for moving towards an Industry 4.0 and lean manufacturing integration

The immaturity of this research area is a natural explanation for why no implementation framework for an Industry 4.0 and lean manufacturing integration has been published in the literature. It is important to gain a more in-depth understanding of how these two domains interact before an implementation framework can be proposed, and the four prior research gaps are all important in this respect.

Numerous implementation frameworks for lean manufacturing have been proposed (Bhamu and Sangwan 2014), and guidelines for implementation of Industry 4.0 are starting to emerge (Hermann, Pentek, and Otto 2016). These existing frameworks can be used as a starting point, similar to the work of Powell et al. (2013), who use existing implementation frameworks for ERP and lean manufacturing as a basis to propose a framework for a concurrent implementation process of the two.

Future research should investigate whether there is a preferred implementation sequence of the two domains. Should Industry 4.0 and lean manufacturing be implemented concurrently or sequentially? If they should be implemented sequentially, which one should be implemented first? Further, how will the performance be affected by a concurrent or sequential implementation? How do environmental factors influence these issues?

6.6 What can we learn from earlier studies?

An interesting research approach that should be explored further is how the findings from studies on earlier technological shifts can be used to support research on Industry 4.0. One example of this approach is the review by Maghazei and Netland (2017), who examine how existing literature on AMTs can support the current stream of Industry 4.0 research.

In addition to the existing stream of research on lean automation, another example of an interesting field to explore is the research related to radio frequency identification (RFID) technologies and lean manufacturing. Parts fitted with a RFID chip can, by using tracking equipment, be traced throughout the supply chain (Powell and Skjelstad 2012), and the usage of RFID thus has conceptual similarities with Industry 4.0. Patti and Narsing (2008) investigate the compatibility of lean manufacturing and RFID by asking whether they are competitive or compatible; they argue that RFID can coexist with and support lean implementations. Rafique et al. (2016) investigate how an introduction of RFID technology affects lean implementation barriers. They argue that the capabilities of RFID, such as *real-time traceability* and *automated information visibility*, might help overcome several of the stated lean implementation barriers.

Researchers are therefore encouraged to, in addition to the other areas outlined above, investigate the existing knowledge in adjacent areas to discover how existing findings, propositions, and theories can be transferred to an Industry 4.0 setting. Sometimes, the answers to the future lie in the past.

7. Conclusion

Despite the rapidly increasing popularity of Industry 4.0, no study has so far gathered and presented the scattered literature on how Industry 4.0 relates to the popular field of lean manufacturing. The current article has proposed a conceptual framework that can be used to classify the studies published so far and has given an overview of the current findings and research gaps. The literature findings are classified into four research streams: (1) *Industry 4.0 supports lean manufacturing*, (2) *lean manufacturing supports Industry 4.0*, (3) *performance*

implications of an Industry 4.0 and lean manufacturing integration, and (4) the effect of environmental factors on an Industry 4.0 and lean manufacturing integration. It is clear from the findings that this area is still immature, with seemingly no common platform of knowledge to build the research on. The current article proposes further research in the following five areas: *(1) the impact of Industry 4.0 on 'soft' lean practices, (2) the facilitating effect of lean manufacturing on Industry 4.0 implementations, (3) empirical studies on the performance implications of an Industry 4.0 and lean manufacturing integration, (4) the effect of environmental factors on the integration of Industry 4.0 and lean manufacturing, and (5) implementation framework for moving toward an Industry 4.0 and lean manufacturing integration.* The current article should be seen as the first step to converge this new field of research by establishing a framework that can be used as a foundation for future studies and giving a research agenda, which by pointing out the most apparent research gaps, can inspire and guide future research efforts.

7.1 Contribution to theory

As the first systematic literature review in this area, the current article provides a thorough presentation of the current literature and theoretical standpoints regarding the link between Industry 4.0 and lean manufacturing. The conceptual framework presented in Section 3 describes the relationships between the main constructs investigated in this study and is supported by the literature findings. The current body of research has mainly focused on how Industry 4.0 technologies can be used to support existing lean practices, with most of the emphasis on Andon and Kanban. Most of the studies investigating the performance implications of such an integration claim that increased flexibility will be the main benefit, similar to what the proponents of Industry 4.0 claim it will entail. Although there are no studies explicitly discussing the applicability of an integrated Industry 4.0 and lean manufacturing system in different environments, most use cases are reported from repetitive production environments.

The proposed research agenda guides future research efforts based on what the current research insufficiently addresses or answers. It encourages researchers not only to focus on how Industry 4.0 can enhance the technical solutions of lean manufacturing, but also how it impacts the 'soft' aspects of lean. The effects of established lean manufacturing systems on the ease of implementing Industry 4.0 are another important research area, one relevant for a large number of companies aiming to transform their operations using the emerging ICT solutions. There is also a call for additional empirical research regarding the actual performance benefits of such an integrated solution, together with a future need for synthesising the knowledge into an implementation framework.

7.2 Contribution to practice

A literature review offers a quick introduction to the current body of knowledge and is thus a helpful tool for practitioners seeking the most recent research findings. Table 5 can be used as a starting point for practitioners wishing to investigate how the emerging ICT solutions associated with Industry 4.0 can be used to enhance lean practices. Table 6 gives an indication

of which performance metrics are affected through an Industry 4.0 and lean manufacturing integration and will thus work as a reference point for practitioners seeking to improve specific performance areas. Similarly, Table 7 gives an overview of the sectors where the implementations of integrated solutions have been reported in the literature.

7.3 Limitations

The limitations of the current study must also be highlighted. Although using a systematic literature review approach using five different scholarly databases, some studies might have been overlooked because of the researchers' choice of search terms and databases. There were also some articles excluded because they were not in English, ones that might have contained relevant findings. Lastly, the small number of articles dealing with an Industry 4.0 and lean manufacturing integration is not ideal when aiming towards drawing general conclusions.

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Appendix 1:

Table A1: Search key words (“Part 1” AND “Part 2”)

Part 1	Part 2
<p>"Industry 4.0" OR "Industrie 4.0" OR "the fourth industrial revolution" OR "the 4th industrial revolution" OR "smart manufacturing" OR "smart production" OR "smart factory" OR "smart factories" OR "cyber physical system" OR "cyber physical production system" OR "internet of things" OR "industrial internet" OR "big data" OR "digitalization" OR "digitization" OR "digitalisation" OR "digitisation"</p>	<p>"lean manufacturing" OR "lean production"</p>