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The complementary effect of lean manufacturing and digitalisation on operational performance

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ABSTRACT

The most recent trend manufacturers have embraced to seek operational performance improvements is the use of a wide range of digital technologies typically associated with Industry 4.0. However, few studies have investigated the relationship between such technologies and the long-established lean manufacturing domain, and how they, together, influence operational performance. Based on data from a cross-sectional survey of manufacturing companies, this study investigates the relationships between the use of lean manufacturing, factory digitalisation, and operational performance using hierarchical multiple regression analysis. While simultaneously controlling for the effects of production repetitiveness, company size, and length of lean manufacturing implementation, the findings show that both lean manufacturing and factory digitalisation individually contribute to improved operational performance. Furthermore, it is found that when used together, they have a complementary (or synergistic) effect that is greater than their individual effects combined. These research findings provide both theoretical and practical insights into how lean manufacturing and factory digitalisation affect the operational performance of manufacturing firms. In light of the upcoming fourth industrial revolution, these findings suggest that lean manufacturing is not obsolete but rather is more important than ever in order to reap the benefits from emerging technologies and translate them into improved operational performance.

1. Introduction

Today's market is characterised by shorter product life cycles and the increasing individualisation of products. Together with increasing global competition, this puts pressure both on manufacturing companies' flexibility and on resource efficiency to meet customer demand and stay competitive (Lasi et al. 2014). To meet these challenges, manufacturing companies are forced to continuously seek new approaches to improve their operational performance. *Lean manufacturing* has in the last two decades arguably been the most prominent methodology for improving the operational performance in manufacturing companies (Holweg 2007; Found and Bicheno 2016). Built on the simple idea of eliminating waste in all forms by focusing on the activities that create value for the customer (Womack and Jones 1996), it is a low-tech continuous improvement approach that focuses on employee empowerment and the streamlining of manufacturing activities. Recently, the technology-oriented *Industry 4.0* concept is being branded as the next enabler of performance improvement. The rapid advances in information technology (IT), related to both hardware

and software, have enabled a potential revolution in the manufacturing industry, commonly known as Industry 4.0 (Kang et al. 2016). The Industry 4.0 vision refers to networks of autonomous manufacturing resources that are sensor-equipped and self-configuring and is enabled by the integration of a large number of different digital technologies (Kagermann et al. 2013). In general, this increased use of digital data and digital technologies is typically referred to as *digitalisation* (Buer, Fragapane, and Strandhagen 2018).

The origins of lean manufacturing can be traced back to 1948 (Holweg 2007), and lean manufacturing in its purest form works completely independent of any kind of IT. The opinion that IT and lean manufacturing are incompatible has been prevalent in both academia and industry for a long time (Pinho and Mendes 2017). This notion can be traced back to the reflections by Sugimori et al. (1977), who claimed that using computerised systems for material planning increases cost, reduces transparency, and leads to overproduction of goods. Lean manufacturing utilises decentralised control by giving local autonomy to the employees and

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emphasises simplicity and transparency. In a lean manufacturing system, any problems should be handled immediately, preferably by taking care of the root cause of the problem (Åhlström, Kosuge, and Mähring 2016). In contrast, IT focuses on creating a centralised database and 'a single version of the truth,' which creates a disconnect between the reality on the shop floor and the abstract information generated by the IT system. The advanced algorithms found in the IT systems can reduce the perceived simplicity of a process and reduce the transparency of decision-making. This increased complexity and reduced transparency can create distance between the decision-maker and the decision-making process. Furthermore, IT systems are rigid, complex, and difficult to change and continuously improve, thus encouraging workarounds instead of handling the root cause of problems (Åhlström, Kosuge, and Mähring 2016). Although lean manufacturing and Industry 4.0 share the same objective of improved performance, these underlying contradictory aspects might complicate a concurrent use.

On the other hand, others advocate that technology can be integrated into a lean manufacturing system as long as it supports lean principles and adds value to the process. The introduction of cyber-physical systems (CPS) and the Internet of Things (IoT) enable distributed computing and autonomy not typically found in traditional centralised IT systems (Buer, Strandhagen, and Chan 2018; Ghobakhloo 2020). Does this suggest that Industry 4.0 should be seen as a complementary approach that can support and address limitations in existing lean manufacturing systems?

Currently, there exists only scattered, non-conclusive research on the relationship between Industry 4.0 and lean manufacturing. There is especially a lack of empirical studies investigating the performance implications of an Industry 4.0 and lean manufacturing integration (Buer, Strandhagen, and Chan 2018). Although some studies recently have studied the performance implications of such an integration, there are disagreements in the literature regarding how lean manufacturing and Industry 4.0 interact to impact performance. Some studies suggest that lean manufacturing is a mediator of the relationship between the implementation of Industry 4.0 and performance (e.g. Tortorella et al. 2018; Kamble, Gunasekaran, and Dhone 2020). Another study suggests that Industry 4.0 is a moderator of the relationship between lean manufacturing and operational performance (Tortorella, Giglio, and van Dun 2019), while other studies investigate their supportive effects without hypothesising which of the two is the moderator (e.g. Tortorella and Fettermann 2018; Rossini et al. 2019). Pinho and Mendes (2017) further emphasised the value of a

study investigating the interaction between lean manufacturing and technology in a varied context, both in terms of industry characteristics and company size.

Motivated by the disagreements in literature and the scarcity of studies investigating this issue in the context of a developed country, this paper seeks to investigate and clarify how lean manufacturing and factory digitalisation interact, and which impacts these two domains have on operational performance. Unlike previous studies, we extend this study to further investigate whether lean manufacturing and factory digitalisation can be considered as complementary resources. This paper draws on existing literature to develop and validate a research model through a cross-sectional survey of Norwegian manufacturing companies. To the best of our knowledge, this is one of the first studies to investigate these issues, especially in the context of a developed country. By assessing the complementarity between lean manufacturing and factory digitalisation, this study thus shows that digital technologies can facilitate the operational performance benefits of lean manufacturing systems, and, at the same time, lean manufacturing systems can promote the success of digital technologies. These findings present important contributions to theory aimed at addressing the research gaps outlined above. Furthermore, this study presents valuable managerial insights by indicating how managers should approach the fourth industrial revolution, and which role existing lean manufacturing systems will play in this transition.

This paper is structured as follows: Section 2 introduces relevant literature and develops the research hypothesis. Section 3 describes the research method utilised in this paper, while Section 4 presents and discusses the research findings. Finally, Section 5 concludes the paper and highlights its contributions.

2. Theoretical background and hypothesis development

2.1. Lean manufacturing and operational performance

Lean manufacturing aims at reducing waste and non-value-added activities (Womack, Jones, and Roos 1990). Internally, in production, this is manifested through, among other things, streamlined, stable, and standardised processes; minimal inventories; the one-piece flow of products; production based on actual downstream demand; short setup times; and employees being involved in continuous improvement efforts (Chavez et al. 2015). All these aspects can support improvements in different dimensions of operational performance, such as product

quality and production cost, lead time, flexibility, and reliability (Marodin and Saurin 2013).

Since lean manufacturing was popularised and became a mainstream management approach, there have been numerous studies aiming at measuring the actual effect of lean manufacturing on operational performance (Ciano et al. 2019). Krafcik (1988) coined the term *lean* and presented one of the first studies to compare lean manufacturers with typical mass-production manufacturers. Mackelprang and Nair (2010) did a meta-analysis of 25 articles investigating the relationship between lean manufacturing practices and performance. While the operationalisation of lean manufacturing practices and operational performance tends to vary between studies, the consensus is that the adoption of lean manufacturing is positively associated with operational performance improvement (Mackelprang and Nair 2010; Marodin and Saurin 2013).

2.2. Digitalisation of manufacturing and operational performance

The increased digitalisation of manufacturing operations is expected to cause disruptive changes in industrial manufacturing. It can enable new and more efficient processes and new products and services (OECD 2017), and it is expected to lead to significant changes in organisational structures, business models, supply chains, and the manufacturing environment (Kagermann et al. 2013; Lasi et al. 2014; Hahn 2020). Emerging digital technologies will provide disruptive changes to the technologies we know today and will especially improve the integration between the different systems (Liao et al. 2017; Xu, Xu, and Li 2018; Winkelhaus and Grosse 2020). Today, the vision of a fourth industrial revolution is emerging, popularly known as Industry 4.0 (Lasi et al. 2014). Industry 4.0 started as a German government programme to increase the competitiveness of their manufacturing industry (Kagermann et al. 2013). 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 has been 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 (Hofmann and Rüsch 2017; Moeuf et al. 2018). Today, Industry 4.0 can be described as an umbrella term, referring to a range of current concepts and touching several disciplines within industry (Lasi et al. 2014). It can be broadly defined as a vision for the future of manufacturing where a smart manufacturing environment is created by utilising a large number of emerging, digital technologies.

Industry 4.0 is a general term, encompassing an increasing number of different technologies. While it is challenging to scope a 'moving target' such as Industry 4.0, this paper mainly focuses on the part of Industry 4.0 we refer to as *factory digitalisation*. In many ways, digitalisation is a broader term than Industry 4.0 since it has impacted and will continue to impact the whole society for years. In the widest sense, digitalisation of production can be defined as 'the use of digital data and technology to automate data handling and optimise processes' (Buer, Fragapane, and Strandhagen 2018, 1036). It is especially related to autonomous data collection and analysis, as well as interconnectivity between products, processes, and people (Buer, Strandhagen, and Chan 2018; Sjøbakk 2018). While Industry 4.0 can be described as a vision of how manufacturing will be done in the future, factory digitalisation is seen as a key enabler of getting there (Pfohl, Yahsi, and Kurnaz 2017). Factory digitalisation refers to the digitalisation of the production process, through, for example, the use of digital sensors and IoT technology. Together with the use of advanced enterprise software, it can enable a real-time view of the production process (Kagermann et al. 2013). The integration of the vertical value chain, that is, from product development to production, as well as fully integrated planning, from sales forecasting to production, are other aspects that characterise a digitalised factory (Kagermann et al. 2013). One of the arguments for focusing on factory digitalisation instead of the full-scale Industry 4.0 vision is because most manufacturing companies are still in the early stages regarding the implementation of Industry 4.0 technologies, and are thus at a more basic level of IT usage than we typically associate with Industry 4.0 (Bley, Leyh, and Schäffer 2016; Van den Bossche et al. 2016; Moeuf et al. 2018).

Early research on the use of IT in organisations showed what we now know as the productivity paradox (Brynjolfsson 1993). This paradox highlights the apparent lack of a relationship between IT investments and productivity gains. IT requires large investments in hardware, infrastructure, and software. Standard packages from software vendors typically do not fit the complex characteristics of different production environments, necessitating alterations to the software or the production process itself. All these are aspects that imply that succeeding with IT investments is not a straightforward task, requiring extensive and careful planning.

However, with time, the productivity paradox faded away, and Bharadwaj (2000) found a positive association between IT capability and firm performance. Later, McAfee (2002) found that the implementation of an

enterprise resource planning (ERP) system had positive effects on operational performance. Raymond and St-Pierre (2005) found that the use of advanced manufacturing systems was significantly associated with both operational and business performance. Similarly, Khanchanapong et al. (2014) found a positive association between the use of manufacturing technologies and cost, quality, lead time, and flexibility performance.

Moeuf et al. (2018) reviewed different cases from the literature reporting on Industry 4.0 pilot projects and found that the most commonly reported performance benefits were increased flexibility, improved productivity and quality, and reduced cost and delivery time. Using secondary data from a survey of the Brazilian industry, Dalenogare et al. (2018) investigated the effects of some of the emerging technologies typically associated with Industry 4.0. They found that the following technology groups had a positive association with operational performance: *computer-aided design with computer-aided manufacturing, digital automation with sensors,* and *big data.* In contrast, the group *additive manufacturing* had a negative association with operational performance. As shown, numerous earlier studies have investigated the effects of lean manufacturing and technologies on performance separately. However, the main objective of this study is to investigate how they interact to impact operational performance.

2.3. The interaction between lean manufacturing and digitalisation

Although some skepticism has been raised regarding the compatibility of lean manufacturing and IT solutions in the past, more studies have recently focused on the benefits of combining these two domains (Riezebos, Klingenberg, and Hicks 2009; Pinho and Mendes 2017). Lean manufacturing combined with ERP (Powell et al. 2013), MES (Cottyn et al. 2011), advanced manufacturing technologies (AMTs) (Boyer et al. 1997), simulation (Goienetxea Uriarte, Ng, and Urenda Moris 2020), and radio frequency identification (RFID) (Brintrup, Ranasinghe, and McFarlane 2010) have been investigated in different studies and found to have operational benefits.

In light of the technological developments associated with Industry 4.0, the relationship between lean manufacturing and technology has again become an area of research interest (Buer, Strandhagen, and Chan 2018; Gupta, Modgil, and Gunasekaran 2020; Núñez-Merino et al. 2020). Do emerging digital technologies, increased automation levels, and less dependence on human labour mean that lean manufacturing will now become obsolete? Alternatively, will lean manufacturing be more important

than ever as a framework for the successful deployment of emerging technologies into manufacturing?

Since research on this relationship accelerated in 2016, studies have moved slowly from purely conceptual studies towards more empirical-based studies (Buer, Strandhagen, and Chan 2018). Discussing this interaction on a conceptual level, Sanders et al. (2017) argue that the concept of lean manufacturing will not fade away but rather will become more important for a successful Industry 4.0 implementation. They claim that most lean manufacturing tools will benefit from the introduction of Industry 4.0, while some lean manufacturing tools can also be facilitators or even prerequisites for a move towards Industry 4.0. They especially highlight *total productive maintenance (TPM), Kanban, production smoothing, autonomation,* and *waste elimination* as aspects of lean manufacturing that will benefit from introducing digital technologies. Furthermore, they suggest that *real-time capability, decentralisation,* and *interoperability* are the aspects of the Industry 4.0 vision that will offer the most support to lean manufacturing. Kolberg, Knobloch, and Zühlke (2017) present some practical cases of how CPS can be used for continuous improvement, as well as showing how it can enhance the lean manufacturing tools Kanban and Andon. Similar studies evaluating the potential interfaces between Industry 4.0 technologies and lean manufacturing practices are now being published regularly (e.g. Rosin et al. 2019; Tortorella et al. 2020).

Recently, empirical-based studies investigating the performance impact of the concurrent use of lean manufacturing and Industry 4.0 have started to emerge. Through a survey of Indian manufacturing firms, Kamble, Gunasekaran, and Dhone (2020) found that the implementation of lean manufacturing practices has a full mediating effect on the relationship between Industry 4.0 technologies and sustainable organisational performance. Their results indicate that Industry 4.0 technologies in itself do not contribute to improved performance, but rather that these technologies are enablers of lean manufacturing.

Through a survey of Brazilian manufacturers, Tortorella and Fettermann (2018) found indications that a concurrent implementation of lean manufacturing and Industry 4.0 leads to larger performance improvements. Later, Rossini et al. (2019) conducted a study with a similar research design in European manufacturers. Their findings suggest that manufacturers that aim to adopt Industry 4.0 should concurrently implement lean manufacturing as a way to support process improvements. However, when investigating this relationship, neither of these studies used control variables to control for systematic biasing effects, which could impact the validity of the

results. In another study of Brazilian manufacturers, Tortorella, Giglio, and van Dun (2019) investigated the moderating effect of some Industry 4.0 technology groups on the relationship between certain aspects of lean manufacturing and operational performance. Their results indicated that product and service-related technologies positively moderated the relationship between continuous flow and operational performance, while process-related technologies negatively moderated the relationship between setup time reduction and operational performance. However, the design of the study did not control for factors such as production repetitiveness or length of the lean manufacturing programme, which might have influenced the results. Furthermore, as pointed out by the authors, socio-economic factors might also have influenced the results.

As shown, earlier studies are not unanimous regarding the nature of the relationship between lean manufacturing and emerging digital technologies and their combined effect on performance. Furthermore, Ghobakhloo and Hong (2014) pointed out that the dynamic nature of IT, with its rapid developments, necessitates updated studies investigating and clarifying its relationship with lean manufacturing. This study further investigates the interaction between lean manufacturing and factory digitalisation and its relationship with operational performance. We hypothesise that these are complementary approaches and propose the following hypothesis:

> Hypothesis: Lean manufacturing and factory digitalisation are complementary resources that produce synergistic effects on operational performance.

3. Research method

3.1. Sampling

The empirical data used in this study were collected through a survey distributed to Norwegian manufacturers. The initial sample consisted of all the manufacturing companies which were on the mailing list of a knowledge-sharing platform for manufacturing logistics. This initial sample consisted of 212 Norwegian manufacturing companies, representing a wide range of sectors and company sizes. To the best of our knowledge, the initial sample reflects the Norwegian industry with a relatively high proportion of project-based manufacturing (Norwegian Ministry of Trade' Industry and Fisheries 2017). The link to the survey was distributed through e-mail, and a total of 76 responses were collected through an online survey tool. Of these, one of the returned responses lacked answers for several questions and was therefore removed from the final sample. This study thus ended up with a final sample of 75 respondents and a response rate of

Table 1. Demographics of the final sample ($n = 75$)

		Sample (%)
Industrial sector	Machinery	18.7%
	Chemical	16.0%
	Fabricated metal products	12.0%
	Food & beverage	9.3%
	Electronics	9.3%
	Furniture	6.7%
	Fabricated wood products	6.7%
	Shipyard	6.7%
	Automotive	5.3%
	Other	9.3%
Respondent's profile	Production manager	29.3%
	CEO	20.0%
	CTO	10.7%
	Improvement manager	10.7%
	Supply chain manager	9.3%
	Project manager	5.3%
	Other	14.7%
Production repetitiveness	Highly non-repetitive	33.3%
	Non-repetitive	21.3%
	Repetitive	26.7%
	Highly repetitive	18.7%
Company size	Small enterprise	12.0%
	Medium-sized enterprise	36.0%
	Large enterprise	52.0%
Length of lean implementation	No lean programme	12.0%
	< 1 year	12.0%
	1–5 years	34.7%
	> 5 years	41.3%

35.4%. This sample size is comparable to earlier, similar studies (e.g. Tortorella and Fettermann 2018; Kamble, Gunasekaran, and Dhone 2020), but is conducted in Norway which is a small country with a corresponding small manufacturing base (Norwegian Ministry of Trade' Industry and Fisheries 2017). The survey was sent to a management representative in the company — typically the chief executive officer (CEO), chief technology officer (CTO), production manager, or someone in a similar position. They were asked to assess the factory in which they are working, and these employees were assumed to have the required knowledge themselves or the ability to seek answers from other company representatives to answer the questions in all the categories reliably. Table 1 shows the demographics of the sample.

3.2. Operationalisation of constructs

3.2.1. Predictor variables
Because of the ambiguity surrounding the concept of lean manufacturing, Mackelprang and Nair (2010) suggest using multi-item scales to survey lean manufacturing practices. In this study, the operationalisation of lean manufacturing is based on the work of Shah and Ward (2007). This operationalisation is well proven and has been used in numerous other studies, either directly or in an adapted form (e.g. Azadegan et al. 2013; Godinho Filho, Ganga, and Gunasekaran 2016; Tortorella and Fettermann 2018). This study focuses on the aspects of lean

manufacturing that are related to the internal manufacturing process, known as *internal lean practices* (*ILPs*). The six ILPs defined by Shah and Ward (2007) are *pull production, continuous flow, setup time reduction, statistical process control* (*SPC*), *TPM,* and *employee involvement*. Although individual ILPs may be used in isolation for performance improvements, the true power of lean manufacturing comes when the practices are implemented together and support each other (Shah and Ward 2003). This operationalisation consists of 24 measures in which five-point Likert scales were used to assess the degree of implementation, ranging from *1 — no implementation* to *5 — complete implementation*. Based on this, we created six summated scales corresponding to the six mentioned ILPs. The overall *lean manufacturing score* is the average of the six individual ILPs.

Regarding Industry 4.0 and digitalisation, established measurement scales are scarce. Within this topic, there is still some confusion surrounding the domain, both in content and semantics (Buer, Fragapane, and Strandhagen 2018; Moeuf et al. 2018). The 'Industry 4.0 Self-Assessment' model (Geissbauer, Schrauf, and Hentrich 2015) presents a wide range of assessments in six different dimensions, some of which are highly relevant to the scope of this study. It provides detailed explanations on each question and presents illustrating examples. As this study focuses on the digitalisation of production, which includes the digitisation, integration, and automation of data flows, this model was used as a foundation for the survey instrument. Questions were extracted from this measurement instrument based on their relevance to internal factory digitalisation. In total, six measures were used, in which companies were asked to rate their digitalisation degree on a five-point Likert scale. Because these are emerging technologies, and are not necessarily easily comprehensible, extended explanations were supplied along with each question. The factory digitalisation score was calculated as the average of the responses to these six questions.

3.2.2. Dependent variable

As suggested by Slack, Chambers, and Johnston (2010), the measure for operational performance in this study comprised five key performance dimensions: *speed, quality, flexibility, dependability,* and *cost*. This was operationalised into the operational performance indicators *production lead time, product quality, process flexibility, process uptime,* and *production cost per unit*. To assess their level of operational performance, the companies were asked to rate their performance as compared to their direct competitors. This was rated on a five-point Likert scale from *1 — much worse* to *5 — much better*. This approach has been widely applied in similar studies in the past (e.g. Prajogo and Olhager 2012; Zelbst et al. 2014; Chavez et al. 2015). The operationalisation of lean manufacturing, factory digitalisation, and operational performance can be found in the Appendix (Table A1 and Table A2).

3.2.3. Control variables

To control for systematic biasing effects (Ketokivi and Schroeder 2004), we decided to include three control variables in the regression. Previous research has shown that several environmental factors can influence the applicability and performance benefit of lean manufacturing and digitalisation. This includes the repetitiveness of the production environment (White and Prybutok 2001; Shah and Ward 2003; Khanchanapong et al. 2014), company size (White, Pearson, and Wilson 1999; Shah and Ward 2003; Khanchanapong et al. 2014; Sommer 2015), and the length of lean implementation (Agus and Iteng 2013; Wickramasinghe and Wickramasinghe 2017; Tortorella and Fettermann 2018). To determine their degree of production repetitiveness, the respondents were supplied with the descriptions of four different types of production environments presented in Jonsson and Mattsson (2003). These four alternatives were then coded into a four-point scale consisting of 1) *highly non-repetitive production,* 2) *non-repetitive production,* 3) *repetitive production,* and 4) *highly repetitive production*. Following the definitions from the European Commission (2003), companies were ranked as either a 1) *small-sized enterprise* (i.e. < 50 employees and ≤ €10M in turnover), 2) *medium-sized enterprise* (i.e. < 250 employees and ≤ €50M in turnover), or 3) *large enterprise* (i.e. either ≥ 250 employees or > €50M in turnover). To measure the length of lean implementation, respondents were asked to state the time since they started a formal lean programme. This was measured on a four-point scale: 1) *No formal lean program,* 2) *< 1 year,* 3) *1–5 years,* or 4) *> 5 years*. The research framework for this study is illustrated in Figure 1.

3.3. Scale validity and reliability

The survey instrument was validated by investigating three aspects: *content validity, construct validity,* and *reliability*. To ensure content validity, a draft questionnaire was pre-tested by two independent academics with experience in both research projects and industry. Additionally, the questionnaire was based on well-tested and recognised items that have been used successfully in other studies. To assess the construct validity, we considered two aspects: *convergent validity* and *discriminant* validity (Forza 2002). To assess convergent validity, we first investigated the *unidimensionality* of
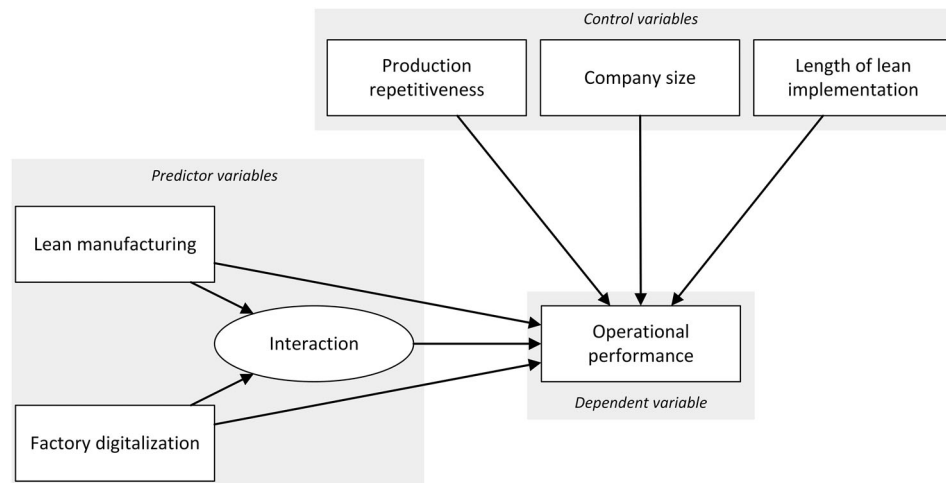
Figure 1. Research framework

Table 2. The means, SDs, and bivariate correlations

| | Mean | SD | Correlations | | | | |
			1	2	3	4	5
1. Production repetitiveness	2.31	1.13	–				
2. Company size	2.40	0.70	0.048	–			
3. Length of lean programme	3.05	1.01	0.045	**0.257***	–		
4. Lean manufacturing	3.02	0.67	**0.253***	0.120	**0.423*****	–	
5. Factory digitalisation	2.93	0.68	0.151	0.092	**0.405*****	**0.645*****	–
6. Operational performance	3.43	0.48	0.045	0.031	0.080	**0.422*****	**0.420*****

Notes: *$p < 0.05$; *** $p < 0.001$.

the measures through principal component analysis. Following the recommendations of Carmines and Zeller (1979), the items for each of the constructs were analysed separately. For all of the constructs, the Kaiser-Meyer-Olkin measure of sampling adequacy was above the recommended limit of 0.5 and Bartlett's test of sphericity returned p-values below 0.001. For each of the independent constructs, the items loaded on a single factor, the eigenvalue exceeded 1.0, the total variance explained exceeded 50%, and all the items' factor loadings were above 0.5, supporting unidimensionality. As additional tests of convergent validity, the *average variance extracted* (AVE) and *composite reliability* (CR) were calculated. The recommended thresholds for good convergent validity for these two tests are AVE > 0.5 and CR > 0.7 (Hair et al. 2010). For the independent variables, the values are above the recommended variables. The dependent variable, operational performance, is composed of multiple, disparate performance dimensions. This means that the loading factors and consequently, AVE and CR will necessarily be somewhat lower for this construct, but still acceptable, as previously proposed by Prajogo and Olhager (2012). To assess *discriminant validity,* we followed the recommendations of Fornell and Larcker (1981). They recommend that to ensure discriminant validity, the AVE for each construct should

be greater than the square of the construct's bivariate correlations (Table 2) with the other constructs. In all cases, this criterion was satisfied. Based on these tests, we assumed sufficient construct validity. To test reliability, the Cronbach's alpha coefficient was calculated for each of the summated scales. All the summated scales have values above the recommended threshold of 0.6 (Forza 2002) and, accordingly, should be reliable for further analysis. The results from the scale validation can be found in the Appendix (Table A1 and Table A2).

To examine the possible non-response bias, we compared the responses to the three control variables: production repetitiveness, company size, and length of lean implementation, as well as five random questionnaire items between the early and late respondents. The chi-square tests for all eight indicated no statistically significant difference between the early and late respondents, with a significance of 0.05. This indicates the absence of non-response bias (Khanchanapong et al. 2014; Chavez et al. 2015).

In order to control for common method bias, we used a two-step approach. First, we designed the questionnaire according to the guidelines of Podsakoff et al. (2003). This included separating the dependent variables from the independent variables in the questionnaire

and emphasising to the respondents that their responses would be kept anonymous. Furthermore, the questionnaire was sent out to management representatives in the companies, who are assumed to be appropriate key informants. In addition to these preventive measures for common method bias, the collected data were analysed using Harman's single-factor test. This was done by loading all the independent and dependent variables into an exploratory factor analysis. The test resulted in 9 components with an eigenvalue exceeding 1 and a first factor that explained 32.3% of the variance, well below the recommended threshold of 50% (Podsakoff et al. 2003). Common method bias was therefore assumed not to be a threat in this study.

4. Results and discussion

4.1. Descriptive statistics

The means, standard deviations (*SDs*), and bivariate correlations of the six mapped variables are presented in Table 2. A few key insights can be observed from the correlation analysis. First, the implementation level of lean manufacturing is positively correlated with the production repetitiveness. This indicates that repetitive manufacturing companies generally have a higher degree of lean implementation, which is similar to earlier findings (e.g. White and Prybutok 2001). In contrast, it can be noted that there is no significant correlation between factory digitalisation and production repetitiveness. Earlier, Strandhagen et al. (2017) suggested that digital technologies are more applicable in highly repetitive environments due to these environments' lower complexity and higher standardisation of material flows, facility layout, and product structures, which facilitate the sensorization of the production processes and, in turn, the collection of production data. However, at the same time, highly repetitive manufacturers (e.g. process manufacturers) tend to have been highly automated and integrated for some time already and might not necessarily be that interested in the latest developments branded as digitalisation. Furthermore, they might not be as interested in aspects such as 'smart' products, as they typically produce commodity products where the product price is a significant order winner. Furthermore, nonrepetitive manufacturers are increasingly focusing on the implementation of digital technologies, for instance, Zennaro et al. (2019) pointed out that recent studies on one-of-a-kind manufacturing have put a large emphasis on integration tools and information sharing systems. These factors might explain the lack of a significant correlation between factory digitalisation and production repetitiveness.

Second, the length of the lean programme is significantly positively associated with company size, suggesting that larger manufacturing companies adopted lean manufacturing practices earlier than did the smaller manufacturers.

Third, as expected, there is a significant correlation between the lean manufacturing implementation level and the length of the lean programme. Lean manufacturing implementations take time and organisations need to devote time, effort, and resources. Organisations need time to, among others, increase the awareness of lean, identify and mitigate implementation barriers and adapt the organisational culture (Bhamu and Sangwan 2014). Nevertheless, we do not see a significant correlation between the length of the lean programme and operational performance. Our findings suggest that the implementation level of lean manufacturing practices is a more significant predictor of operational performance than the length of the lean programme itself.

Fourth, there is a significant, strong correlation between lean manufacturing and factory digitalisation, as well as between the length of the lean programme and factory digitalisation. This indicates that these two domains tend to co-exist in manufacturing companies, challenging the idea that they are incompatible. Since the reflections by Sugimori et al. (1977) surrounding the concurrent use of lean manufacturing and IT were made, there have been substantial developments in terms of the capabilities, flexibility, and accessibility of IT systems, as well as in the competence of their users. These findings thus support some of the recent studies probing the compatibility of lean manufacturing and digital technologies in manufacturing, such as that by von Haartman, Bengtsson, and Niss (2016). Combining lean manufacturing and digital technologies can be an effective way to manage production, and weaknesses in one of the systems can be addressed by solutions from the other. In light of the increasing popularity surrounding digitalisation, these findings indicate that it should not necessarily be the case that *either* factory digitalisation *or* lean manufacturing is implemented but rather that these domains work together.

Finally, we see that operational performance is significantly correlated with both lean manufacturing and factory digitalisation. This is as expected based on the results of previous studies. In the next section, we will look further into these relationships.

4.2. The effects on operational performance

The effects of lean manufacturing and factory digitalisation were examined using hierarchical multiple regression analysis. In total, three models were tested. Model 1

Table 3. Results from the hierarchical multiple regression[a]

	Dependent variable: Operational performance		
	Model 1	Model 2	Model 3
Production repetitiveness (Control)	0.041	−0.074	−0.049
Company size (Control)	0.009	0.014	−0.033
Length of lean implementation (Control)	0.076	−0.176	−0.178
Lean manufacturing		**0.326***	**0.305***
Factory digitalisation		**0.290***	**0.235[†]**
Lean manufacturing × factory digitalisation			**0.247***
F-value	0.196	**4.416****	**4.750*****
R^2	0.008	0.242	0.295
Adj. R^2	−0.034	0.188	0.233
Change in R^2		**0.234*****	**0.053***

Notes: † < 0.10; *p < 0.05; **p < 0.01; *** p < 0.001; [a] Standardised regression coefficients are reported.

only looked at the effects of the control variables on the dependent variable (i.e. operational performance). Next, Model 2 added the direct effects of lean manufacturing and factory digitalisation on the dependent variable. Finally, in Model 3, the interaction term (i.e. lean manufacturing × factory digitalisation) was added. The independent variables were mean-centred to avoid non-essential multicollinearity (Cohen et al. 2015). The data was verified to meet the assumptions regarding linearity, homoscedasticity, the independence of error terms, normality of the residuals, and the multicollinearity required for multiple regression analysis (Hair et al. 2010).

As shown in Table 3, Model 1 explains only a negligible amount of the variance in the operational performance. This suggests that neither production repetitiveness, company size, nor the length of the lean programme in itself contributes to competitive operational performance and that other factors are responsible for this variance. Adding the two hypothesised predictors (Model 2) and the interaction term (Model 3) produced significant improvements to the model (cf. the change in R^2). Model 2 shows significant relationships between both lean manufacturing and factory digitalisation and operational performance. Furthermore, Model 3 shows a significant interaction effect between lean manufacturing and factory digitalisation. The presence of an interaction effect suggests that the two independent variables produce a synergistic effect on the dependent variable (Jeffers, Muhanna, and Nault 2008). The inclusion of lean manufacturing and factory digitalisation, as well as their interaction effect, resulted in a total change in R^2 of 0.287 (i.e. the difference in R^2 between Model 1 and Model 3), suggesting that these two domains explain 28.7% of the variance in operational performance.

To allow for further interpretation, the interaction effect is plotted in Figures 2 and 3. Based on Model 3, this is done by generating a series of simple regression equations and then calculating the predicted values of the dependent variable at high and low levels of the predictor variables (Aiken, West, and Reno 1991; Dawson

2014). As suggested by Cohen et al. (2015), the high levels were defined as being one *SD* above the mean, while the low levels were defined as being one *SD* below the mean. After plotting the interactions, we conducted simple slope analyses to test whether the slopes of the simple regressions lines differed significantly from zero (Aiken, West, and Reno 1991). Testing the slopes in Figure 2, factory digitalisation was shown to be significantly positively associated with operational performance when the lean manufacturing implementation level is high ($\beta = 0.444, p = 0.005$). However, when the lean manufacturing implementation level is low, no significant relationship between factory digitalisation and operational performance is found ($\beta = 0.025, p = 0.890$). Similarly, when testing the slopes in Figure 3, we found that there is a significant positive relationship between lean manufacturing and operational performance at high values of factory digitalisation ($\beta = 0.514, p = 0.002$). For low values of factory digitalisation, no significant relationship between lean manufacturing and operational performance was found ($\beta = 0.095, p = 0.584$). Overall, the results indicate that factory digitalisation only has a significant positive impact on operational performance when the implementation level of lean manufacturing is also high, and vice versa. This suggests that high performers are concurrently using both lean manufacturing and a digitalised factory.

The configurational theory proposes that different resources can either have an enhancing (or synergistic) relationship, in which one resource magnifies the impact of another resource, or it can have a suppressing relationship, in which one resource diminishes the impact of another (Jeffers, Muhanna, and Nault 2008). The significant, positive relationship between the interaction term and operational performance suggests that the concurrent use of lean manufacturing and factory digitalisation yields a synergistic effect on operational performance. This study shows that the improvements in operational performance when implementing either lean manufacturing or digital technologies in isolation are relatively
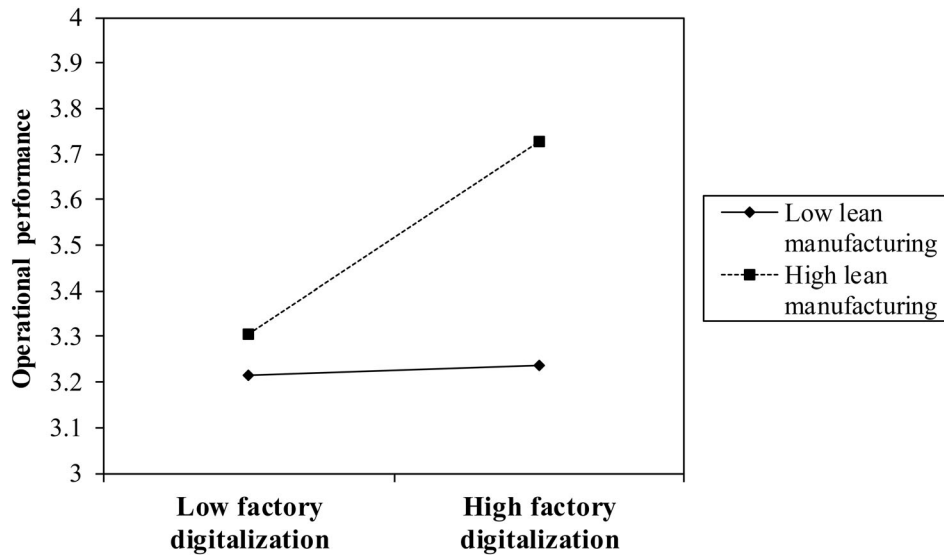
Figure 2. Illustration of the interaction effect between lean manufacturing and factory digitalisation with lean manufacturing as the moderator
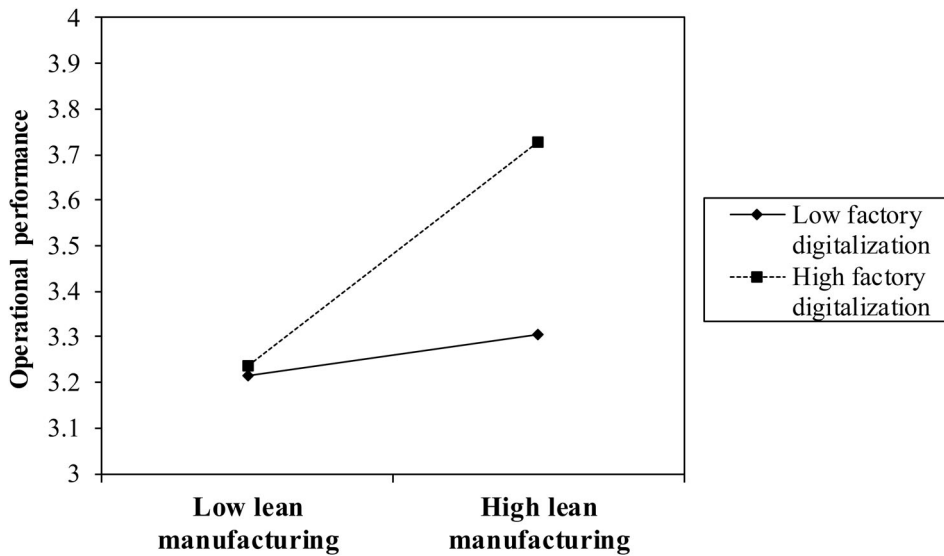
Figure 3. Illustration of the interaction effect between lean manufacturing and factory digitalisation with factory digitalisation as the moderator

modest. The true operational performance advantage comes when both domains are implemented; in other words, their concurrent use produces a synergistic effect that is larger than the sum of their individual contributions.

Khanchanapong et al. (2014) suggest three requirements that characterise complementary resources: (1) complementary resources are not identical, (2) complementary resources are positively correlated, and (3) complementary resources produce synergistic effects on performance that are greater than their individual effects combined. Through the theory and findings presented in this paper, we suggest that all three requirements

are fulfilled, and we propose that lean manufacturing and factory digitalisation are complementary resources, *supporting the proposed hypothesis*. In contrast to the findings of Kamble, Gunasekaran, and Dhone (2020), which suggested that lean manufacturing has a full mediating effect on the relationship between Industry 4.0 and performance, our findings suggested that both lean manufacturing and factory digitalisation individually contribute to operational performance. However, the complementarity between the two domains suggests that joint optimisation results in the largest performance benefits. The findings are in line with the previous findings of Tortorella and Fettermann (2018) and Rossini

et al. (2019). However, this study extends the theoretical model and looks further into the complementarity between lean manufacturing and factory digitalisation.

The finding that lean manufacturing only has a significant impact on operational performance when the level of factory digitalisation also is high might be surprising. This suggests that a basic lean manufacturing system with no digital solutions does not provide any significant competitive advantage in terms of operational performance. To understand this finding, we want to look at it from the resource-based view perspective. The resource-based view argues that a firm can be seen as a bundle of resources (Wernerfelt 1984) and that strategic resources can potentially deliver a sustained competitive advantage to a firm (Barney 1991). *Resources* are defined as 'all assets, capabilities, organisational processes, firm attributes, information, knowledge, etc. controlled by a firm that enable the firm to conceive of and implement strategies that improve its efficiency and effectiveness' (Barney 1991, 101). These resources and how they are combined can be used to explain the differences in performance between different firms. The resource-based view further suggests that individual resources (e.g. lean manufacturing) may have a limited ability to create a competitive advantage in isolation, as it is easier for other companies to imitate (Barney 1995). That lean manufacturing systems create limited competitive advantage in isolation has also been suggested previously by Khanchanapong et al. (2014).

Although this study confirms the complementarity between lean manufacturing and factory digitalisation, it does not identify which domain should be implemented first, or whether they should be implemented concurrently. Several studies have proposed that a successful lean manufacturing implementation should be considered a prerequisite for implementing digital technologies (von Haartman, Bengtsson, and Niss 2016; Klötzer and Pflaum 2017; Buer, Strandhagen, and Chan 2018). Contrarily, we could not find any study that proposes the opposite scenario: using a digitalised factory as a foundation for a successful lean transformation. Proponents of the 'lean first' approach suggest that you should build your manufacturing digitalisation on a stable, standardised, and streamlined production system (Bortolotti and Romano 2012). Through what they call the *integration hypothesis*, MacDuffie and Krafcik (1992) proposed that a lean manufacturing system is a necessary prerequisite for effectively utilising high levels of automation. Having a streamlined production system is vital to avoid automating wasteful activities, as this essentially amounts to the automation of waste creation. Streamlined and standardised processes also simplify the automation process. This is in line with the 'USA principle' of automation,

which stands for *understand, simplify,* and *automate* (Groover 2008). Further, lean thinking assists in highlighting which activities that actually create value for the customer. Digitalisation efforts should reflect the requirements of the customer and should not just be done for the sake of it. By conducting a successful lean transformation in the past, an organisation will have already established a continuous improvement culture that actively drives change and will have embedded problem-solving structures (Davies, Coole, and Smith 2017). These previous improvement efforts could also contribute to reducing employee resistance when management decides to implement new technologies that may threaten their positions.

5. Conclusions

The fourth industrial revolution promises to change the manufacturing landscape, and those who are not able to reap the new technology-induced opportunities are destined to fall behind their competitors. An important area to investigate is the role lean manufacturing will play in this new industrial era. This study has surveyed the use of a number of emerging digital technologies as well as established lean manufacturing practices to investigate their relationship with operational performance in manufacturing. This study identified a strong correlation between users of digital technologies and lean manufacturing practices, suggesting compatibility between the two domains. Both factory digitalisation and lean manufacturing practices were significant positive predictors of the level of operational performance. Furthermore, it was shown that their concurrent use yields even larger performance benefits, suggesting a synergistic relationship between the two domains regarding their impact on operational performance.

5.1. Contributions to theory

This study contributes to research on manufacturing improvement initiatives by investigating the influence of both lean manufacturing and factory digitalisation on operational performance. This study aimed at covering the research gap regarding the interactive effects of lean manufacturing and digitalisation on operational performance previously pointed out by Buer, Strandhagen, and Chan (2018), as well as addressing some of the limitations in the earlier, similar studies.

Lean manufacturing has long been seen as the 'go-to' solution for improved operational performance and creating an improvement culture in the organisation. Rinehart, Huxley, and Robertson (1997, 2) indeed proposed

that lean manufacturing 'will be the standard manufacturing mode of the twenty-first century.' The operational benefits of using lean manufacturing have been proved in numerous previous studies, and the results of the current study support those findings. However, by simultaneously investigating the degree of factory digitalisation, the effect of lean manufacturing can be isolated. This, together with the use of three control variables, further improves the accuracy of the proposed model. The findings from the regression model confirm that lean manufacturing is still a relevant source of competitive advantage. Although many of the ideas and methods in lean manufacturing can be traced far back, the focus on creating value for the customer and eliminating waste are ideas that will not become obsolete, regardless of the technological advances that come about.

While there have been numerous studies on the effects of lean manufacturing on operational performance, studies investigating the effects of digitalisation on operational performance are scarcer. This is especially true when it comes to studies surveying the use of emerging technologies such as IoT and CPS. Contributing to the knowledge in this area, the regression analysis confirmed a significant positive relationship between factory digitalisation and operational performance. This study thus provides evidence that suggests that new, emerging technologies support operational performance improvements and that smart and integrated production processes provide a source of competitive advantage.

Most importantly, this study provides insight and extends the knowledge regarding the relationship between lean manufacturing and factory digitalisation and how they together impact operational performance. We extend earlier studies that have been conducted in the context of developing countries and present one of the first studies to investigate this in the context of a developed country. We also extend the research models used in earlier studies by including additional control variables to make the results more conclusive and increase its generalisability. Different from earlier studies, our findings show that lean manufacturing and factory digitalisation meet the criteria to be considered complementary resources. This indicates that both lean manufacturing and factory digitalisation have a limited ability to generate competitive advantage in isolation. The true competitive advantage becomes evident when both domains are highly implemented and can work together to improve the firm's operational performance. These insights should be used when developing roadmaps for achieving world-class operational performance in manufacturing companies.

5.2. Managerial implications

This study also has several managerial implications. First, it challenges the established opinion that lean manufacturing and IT are incompatible. The findings here actually show the opposite, that the two not only co-exist but also mutually reinforce each other. Most companies embracing the lean paradigm also engage in digitalisation, and vice versa. The industry does not seem to consider the two as mutually exclusive or contradictory. However, a certain share of companies does not seem to see the value of such improvement paradigms, possibly because of a lack of improvement initiatives more generally. As this study has shown, these companies' performance is inferior, and they thus risk losing their competitiveness in the long run. This provides valuable managerial insights and should be used as a support in developing roadmaps for production improvement initiatives.

To achieve the greatest performance benefits, lean manufacturing and digital technologies should be used concurrently. For managers who already have a developed lean manufacturing system in place, this provides valuable insights. We have recently seen examples where companies have cancelled their lean manufacturing programmes in order to put all their attention into pursuing opportunities from emerging digital technologies. Based on our findings, we strongly recommend against this approach. The existing lean manufacturing system should not be neglected but should rather be used as a basis for deploying new technologies into the manufacturing system. For managers who have not yet looked into lean manufacturing, this study shows why it can be a good idea to supplement factory digitalisation efforts with a lean manufacturing system. In an increasingly competitive manufacturing sector, these findings provide valuable managerial insights, as being able to develop production systems tailored to and reflecting the requirements of each unique production environment is an important competitive advantage.

That these two domains seem to be so dependent on each other to create a competitive advantage presents some interesting implications. Earlier research has emphasised that IT resources create limited value on their own and should be used to support and enhance organisational capabilities and business processes (Liang, You, and Liu 2010). As the companies we surveyed were asked to evaluate themselves in comparison to their competitors, our findings suggest that to achieve superior operational performance today, integration of these two domains is essential. A basic lean manufacturing system

with no digital solutions no longer provides any significant operational performance advantage. Similarly, digitalising manufacturing operations that are not aligned with lean thinking and fail to recognise the importance of lean principles and practices is also of limited value. The ability to introduce emerging digital technologies and align them with well-proven lean principles is evidently an important contributor to operational performance.

Although there is a lack of implementation frameworks for integrating lean manufacturing and digitalisation available in the literature (Buer, Strandhagen, and Chan 2018), a few managerial recommendations can be posted. Earlier studies have proposed that lean manufacturing systems remain an excellent foundation that can be used as a basis for deploying emerging digital technologies into a manufacturing system. Moving toward the Industry 4.0 vision should be seen as a stepwise process where different prerequisites should be in place. Klötzer and Pflaum (2017) argued that lean manufacturing remains the basic prerequisite for the digitalisation of manufacturing. Bosch (2018) summarised the process of moving toward Industry 4.0 in three steps: First, a streamlined process as a result of a lean transformation; second, an enabled factory with the required IT architecture; and third, a connected factory taking advantage of the latest technological advancements, such as cloud computing, CPS, and the IoT.

While lean manufacturing probably already has passed its hype peak, the hype surrounding digital technologies might continue to grow. Amara's law states that 'we tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run' (Ratcliffe 2018). This observation might also be accurate for improvement programmes and might explain why some manufacturing and consultancy firms are exchanging their lean implementation programmes for digitalisation programmes. We want to reiterate that manufacturing companies who are yet to implement lean manufacturing should carefully consider whether moving toward Industry 4.0 should be their next step. Our findings indicate that a digitalised manufacturing system without complementary lean manufacturing practices experiences only minor improvements in operational performance.

5.3. Limitations and future research

There are a few limitations to this research that should be noted, as well as some directions for future research. Regarding survey-based research, several limitations are well known. One limitation is the sample population, which was composed solely of Norwegian manufacturers.

Although we expect these results to hold for manufacturers in general, we cannot claim that this is the case. Furthermore, although the respondents were guaranteed anonymity, there might be a social desirability bias in their responses, in which they assess their implementation level and operational performance to be higher than they actually are. However, as the respondents were promised anonymity and would not gain anything from making their responses seem more positive than was really the case, we expect that this is not a major concern in this study. Although the multicollinearity is below the recommended levels proposed, for example, by Hair et al. (2010) and Cohen et al. (2015), the high degree of correlation between lean manufacturing and factory digitalisation might, to some degree, have reduced, the overall R^2 of the regression model, confounded the estimation, and reduced the significance of the regression coefficients. Moreover, although the current sample size did not allow for it, structural equation modelling might further have increased the significance of the proposed regression model. Regarding the scope, this study focused on the internal aspects of lean manufacturing and digital technologies. Other aspects that were not investigated in this study most likely also influence operational performance and could be an area for future research. Last, it is important to emphasize that while the findings in this paper prove significant relationships between the studied variables, this does not necessarily imply causality.

Future research should continue to investigate how technology affects lean organisations and how lean implementation frameworks are affected. While this study looked at lean manufacturing and factory digitalisation as overall concepts, further insight might be obtained through a study of the relationships between individual lean manufacturing practices and individual technologies. Finally, while this study confirmed the complementarity of lean manufacturing and factory digitalisation, future research should investigate how these domains should be combined in practice.

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Appendix

Table A1. Scale validity and reliability for the questionnaire items related to lean manufacturing

		Items	Factor loading	Factor loading
Lean manufacturing AVE = 0.553; CR = 0.880; Cronbach's α = 0.835	**Pull production** AVE = 0.644; CR = 0.876; Cronbach's α = 0.807	Production is 'pulled' by the shipment of finished goods	0.851	0.685
		Production at stations is 'pulled' by the current demand of the next station	0.861	
		We use a 'pull' production system	0.879	
		We use Kanban, squares, or containers of signals for production control	0.582	
	Continuous flow AVE = 0.638; CR = 0.875; Cronbach's α = 0.809	Products are classified into groups with similar processing requirements	0.844	0.609
		Products are classified into groups with similar routing requirements	0.824	
		Equipment is grouped to produce a continuous flow of families of products	0.817	
		Families of products determine our factory layout	0.701	
	Setup time reduction AVE = 0.776; CR = 0.912; Cronbach's α = 0.855	Our employees practice setups to reduce the time required	0.919	0.801
		We are working to lower setup times in our plant	0.915	
		We have low setup times for equipment in our plant	0.803	
	Statistical process control (SPC) AVE = 0.668; CR = 0.909; Cronbach's α = 0.873	A large number of equipment/processes on shop floor are currently under SPC	0.869	0.798
		We extensively use statistical techniques to reduce process variance	0.924	
		Charts showing defect rates are used as tools on the shop floor	0.839	
		We use fishbone diagrams to identify the causes of quality problems	0.741	
		We conduct process capability studies before product launches	0.693	
	Total productive maintenance (TPM) AVE = 0.673; CR = 0.892; Cronbach's α = 0.837	We dedicate a portion of every day to planned equipment maintenance–related activities	0.802	0.789
		We maintain all our equipment regularly	0.790	
		We maintain excellent records of all equipment maintenance–related activities	0.856	
		We post equipment maintenance records on the shop floor for active sharing with employees	0.832	
	Employee involvement AVE = 0.596; CR = 0.854; Cronbach's α = 0.773	Shop floor employees are key to problem-solving teams	0.726	0.761
		Shop floor employees drive suggestion programmes	0.806	
		Shop floor employees lead product/process improvement efforts	0.862	
		Shop floor employees undergo cross-functional training	0.682	

Table A2. Scale validity and reliability for the questionnaire items related to factory digitalisation and operational performance

		Items	Factor loading
Factory digitalisation AVE = 0.501; CR = 0.857; Cronbach's α = 0.793	**Digitalisation of the production process**	To what extent does your IT architecture (hardware) address the overall requirements of digitalisation and Industry 4.0?	0.790
		How advanced is the digitalisation of your production equipment (sensors, Internet of Things [IoT] connection, digital monitoring, control, optimisation, and automation)?	0.626
	Real-time capability	To what extent do you have a real-time view of your production and can dynamically react to changes in demand?	0.692
		To what extent do you use a manufacturing execution system (MES) or similar to control your manufacturing process?	0.699
	Vertical and horizontal integration	How would you rate the degree of digitalisation of your vertical value chain (from product development to production)?	0.737
		To what degree do you have an end-to-end information technology (IT)–enabled planning and control process from sales forecasting, over production to warehouse planning and logistics?	0.692
Operational performance AVE = 0.411; CR = 0.767; Cronbach's α = 0.629	**Throughput time**		0.657
	Product quality		0.356
	Process flexibility		0.568
	Process uptime		0.790
	Production cost per unit		0.742