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ORIGINAL ARTICLE

The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers

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Abstract
This study aims at examining the impact of the interrelation between the adoption of Industry 4.0 technologies and the implementation of lean production (LP) practices on the improvement level of European manufacturers' operational performance. To achieve that, we conducted a survey with 108 European manufacturers that have been implementing LP and initiated their Industry 4.0 adoption. The collected data was analyzed through multivariate techniques, allowing to identify the effect of this relationship according to different contextual factors deemed as influential by previous literature, such as company size, LP implementation experience, type of ownership, and business operating model. Results underpin the idea of a wide applicability of both approaches, indicating that higher adoption levels of Industry 4.0 may be easier to achieve when LP practices are extensively implemented in the company. In opposition, when processes are not robustly designed and continuous improvement practices are not established, companies' readiness for adopting novel technologies may be lower. By comprehending that Industry 4.0 technologies are highly related to LP practices, disregarding the context, managers from EU manufacturers can address the implementation of both approaches in a more assertive way.

Keywords Industry 4.0 · Lean production · European manufacturers · Survey · Lean 4.0

1 Introduction

The wide adoption of lean production (LP) practices and principles has consistently occurred throughout different industries and contexts during the last three decades [1–3]. Such intensive adoption is due to the expected benefits that LP implementation can entail, such as cost reduction, quality and productivity enhancement, delivery, and customer satisfaction improvement [4]. In this sense, a diversity of organizations has been investing a lot of effort to adapt and implement LP in their processes and systems [5, 6].

With the advent of Industry 4.0, new management paradigms have been raised through novel technology adoption [7]. As Industry 4.0 is characterized by modernized information and communication technologies (ICT), products, machines, and processes can become interconnected, allowing the establishment of the "smart factory" concept [8]. In this sense, many authors spotlighted the potential benefits of adopting ICT such as 3D printers, cloud computing, and augmented reality models [9–11], generating great expectations and enthusiasm about the theme. However, literature evidence regarding Industry 4.0's integration into other management approaches, such as LP, is still scarce. Some previous studies [12–14] attempted to examine how some LP practices could benefit from the incorporation of a certain set of technologies. Additionally, other researchers [15, 16] have suggested a positive relationship between LP and Industry 4.0, but literature falls short of empirical validation of such synergy.

Thus, academic evidence on the interrelation between Industry 4.0 and LP is incipient, and much investigation still needs to be addressed in order to better understand whether there is a link between LP and Industry 4.0 (and vice versa) and whether this has an impact on companies' operational performance [17]. Further, prior studies on LP [18, 19] have emphasized the importance of contingencies for properly implementing LP. Nevertheless, the impact of such contingencies on the relationship between Industry 4.0 and LP is quite unknown, highlighting an additional gap in literature.

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Therefore, this study aims at examining the impact of the association between the adoption of LP and Industry 4.0 on the improvement levels of manufacturers' operational performance. We investigate how this association might occur under the effect of five contextual factors deemed as influential by previous researches; they are company size [18], LP implementation experience [20], type of ownership [21], business operating model [22], and technological intensity [23]. To achieve these goals, we performed a survey-based study with 108 European manufacturers that have implemented LP and initiated their Industry 4.0 adoption. The collected data was analyzed through multivariate techniques. Besides its implications to theory, this study contributes to practice as it provides managers evidence on how to look at the two approaches to achieve higher operational performance levels. Further, since this is a cross-sector survey-based study, it enables to understand the pervasiveness of both approaches demystifying unsupported assumptions.

2 Background

2.1 Industry 4.0

Industry 4.0 represents the integration of automation technologies, e.g., cyber physical systems (CPS), collaborative robots, and big data, into production [24]. In this ICT-driven industrial scenario, prominent technological frameworks for productive processes (either internal or external to organization) have been proposed, entailing a variety of countermeasures to the increasingly needs of informatization in manufacturers [8, 25]. Hence, research on Industry 4.0 has been demanded so that novel findings related to its barriers, advantages, and concepts are provided [26].

However, for many manufacturers, the current ICT readiness level may not be enough to bear the adoption of Industry 4.0, whose goal is to integrate operations horizontally and vertically, as well as end to end [27]. Further, Industry 4.0 adoption may impact other key aspects of an organizational structure, such as human resources development [28] and customer relationship management [29]. Thus, although Industry 4.0 technologies may support the achievement of extremely novel performance standards, they might also require fundamental changes in organizations' *modus operandi* which raises an additional challenge for its acceptance. Further, firms generally struggle to determine their actual condition with respect to Industry 4.0 maturity, undermining the clear identification of which actions should be addressed.

Table 1 consolidates the main Industry 4.0 technologies found in the literature. It is noteworthy that, out of the 16 identified technologies, "big data" and "augmented reality" were the most frequently mentioned, with nine citations each. These technologies are widely deemed by the authors due to the potential innovation that they can entail on manufacturing processes [7, 24]. On the other hand, "Collaboration with suppliers/customers through real-time data sharing" appears to be less frequently mentioned in the investigated Industry 4.0 literature. Such fact may denote a lower emphasis that studies on Industry 4.0 are putting on customers/suppliers' relationships.

2.2 Lean production

LP aims at streamlining the flow of value by systemically reducing wastes during the production of a product [2]. It was conceived as an evolutional detachment from Henry Ford's mass production [20]. Although the adoption of LP is not a new concept, few organizations fully understand the philosophy underlying its practices and principles [30]. Based on a people-centric system where people are directly involved in the process of continuous improvements, LP practices are deployed so that employees become active problem solvers [31]. In this sense, each LP practice fits a different purpose and is adapted to solve specific problems. However, there is not a universal definition for the set of LP practices, and academicians often indicate many overlapping ones [32].

LP implementation is usually assumed as a contributor to improving operational performance, in both developed [18, 33, 34] and developing economies' context [34, 35]. However, Lewis [36] claims that the success of LP depends upon the context, resulting in a major barrier for its implementation. Hence, most of the causes attributed to LP failures are associated with changes in internal and external organizational scenarios. Therefore, characteristics of a specific region or country can significantly impact LP implementation and the observed benefits [37].

In this sense, the comprehension of LP systems has significantly evolved during the last few decades. Moving from an exclusive shop floor practice-oriented approach to an integrated and contingency-based value system [38] extends the influence of LP from single firm to the entire supply chain [39]. Overall, the enhanced conceptualization of LP has allowed to better adapt and incorporate LP practices and principles into several sectors that vary from discrete parts manufacturers [40, 41], healthcare [42, 43], construction [44], to public administration [45, 46].

2.3 Industry 4.0 and LP

The association between Industry 4.0 and LP has been increasingly highlighted in operations management research [47, 48]. Over the past few years, researchers and practitioners have started to investigate how both approaches, when implemented together within companies, can raise operational and financial performances to a significantly higher level [13, 15, 23, 49]. In fact, the acknowledgement of the relevant

Table 1 Consolidation of the main Industry 4.0 technologies according to literature

Technologies	Authors										Citation frequency
	1	2	3	4	5	6	7	8	9	10	
Robotic stations on automated production line	X			X				X	X	X	5
RFID tag at working units	X		X		X	X			X		5
Real-time scanning by smartphone or tablet application	X						X		X	X	7
Machines with digital interfaces and sensors	X	X	X		X			X		X	6
Augmented reality	X	X	X	X	X	X		X	X	X	9
Cloud computing system	X	X	X	X	X	X	X				7
Collaboration with suppliers/customers through real-time data sharing					X					X	2
Predictive maintenance through real-time monitoring	X				X					X	3
Artificial intelligence and machine learning algorithms	X	X			X			X	X		5
Production process autonomous management	X	X	X		X	X					5
Digital automation without sensors					X	X				X	3
Sensors for product/operating conditions identification		X			X	X					3
Integrated engineering systems			X			X			X	X	4
Additive manufacturing, rapid prototyping or 3D printing	X	X				X	X		X		5
Big data		X	X	X	X	X	X	X	X	X	9
Internet of Things	X	X	X	X	X	X		X		X	8

Authors: 1-[13], 2-[14], 3-[12], 4-[28], 5-[8], 6-[23], 7-[26], 8-[27], 9-[24], 10-[7]

integration of new technologies into LP has been evidenced in early 1990s and denoted as lean automation (LA). More recently, much attention has been given to LA with the advent of Industry 4.0. In essence, while there are authors advocating that Industry 4.0 can conflict with the ground principles of simplicity, continuous and small improvements from LP, others might claim that such approaches may be positively related.

For instance, Kolberg et al. [14] comment that the existing LA approaches are usually proprietary solutions tailored to individual and specific company needs that might conflict with the usual high-tech and capital-intensive efforts of Industry 4.0. Less skeptical on this relationship, Rüttimann and Stöckli [50] argued that Industry 4.0 initiatives are likely to fail unless they are inserted into a proper scenario that takes into account essential manufacturing laws given by LP. In other words, authors suggest that extensive applications of modern ICT that disregard LP implementation will lead to marginal gains that might frustrate managers in face of the high investment levels carried out. In turn, studies such as Sanders et al. and Wagner et al. [16, 51] provided a more positive view of such relationship. They claim that their integrated implementation may allow companies to overcome traditional barriers in a lean transformation achieving major results.

Despite the different indicatives, studies that investigate this relationship, in general, still lack empirical evidence to support their findings. In fact, Buer et al. [52] have emphasized that the literature on LP and Industry 4.0 is unclear about their association. Additionally, it argues about the necessity of studying the impacts of this relationship on companies' performance and the influence of external factors on the relationship between both approaches. Thus, although this relationship has motivated many studies and practical experimentations, much still need to be understood in order to comprehend its extent [53].

3 Proposed method

3.1 Questionnaire development and data collection

Our research focused on European manufacturers, hence limiting the study sample to these firms. The applied criteria for respondents' selection followed the ones proposed by Tortorella and Fettermann [23]; they were (*i*) respondents should be experienced in LP and (*ii*) respondents should be familiar with Industry 4.0. Further, because of the relatively recent introduction of Industry 4.0 in manufacturers, we did not constrain the sample of respondents in terms of industrial sectors, which entailed a cross-sector dataset. Previous studies [18, 54, 55] on LP have been widely adopting similar strategies for data collection because of the still unknown capillarity of LP practices throughout various industries [56].

Responses to the questionnaire were collected from firms that met those criteria through SurveyMonkey during the months of February, March, and April 2018. The resulting sample comprised 108 valid answers with a response rate of 16.61%, aligned with the 15% rate in similar studies [57]. Then, we verified non-response bias by checking differences in means between respondents of the first e-mail ($n_1 = 43$) and the ones that came after the two follow-ups ($n_2 = 65$) utilizing Levene's test for equality of variances and t test to assess the equality of means [58]. No significant non-response bias was identified between the two groups, with a confidence level higher than 0.95.

Most respondents of the study sample (62.0%) were from smaller companies (≤ 500 employees) and belonged to a family-owned firm (54.6%); 51.9% of them directly delivered to the final consumers (business-to-customer (B2C)), and most companies (57.4%) have started their LP implementation in the last 5 years. Further, 74.1% were from companies located in Italy, and the majority of them (57.5%) were from metal-mechanic sector.

Four parts integrated the questionnaire (see Appendix). First, we collected respondents' demographic information. Second, comprised by 41 questions validated by Shah and Ward [54], we assessed the implementation of LP practices within the companies. Each statement represented one practice that was scored based upon a Likert scale from 1 (fully disagree) to 5 (fully agree). Similar studies on LP have acknowledged this instrument as the basis for their research [59, 60], justifying its application here.

Third, the questionnaire measured the Industry 4.0 technology adoption in each manufacturer. Sixteen items were consolidated based upon the technologies displayed in Table 1. A five-point Likert scale that varied from 1 (not used) to 5 (fully adopted) was applied to each technology. As Industry 4.0 is quite a recent concept that is still being disseminated among manufacturers, we asked companies the adoption level of this technology portfolio (observed variable), avoiding potential misunderstandings related to Industry 4.0 definition.

The final part of the questionnaire evaluated the observed improvement on operational performance during the past 3 years. For that, five performance indicators were used: (i) productivity, (ii) delivery service level, (iii) inventory level, (iv) workplace safety (accidents), and (v) quality (scrap and rework). These indicators were widely applied in similar LP studies that encompassed manufacturing companies [20, 37], since they provide a fair overview of the shop floor performance and are easily linked to shop floor improvements. A five-point scale where 1 meant "worsened significantly" and 5 referred to "improved significantly" was applied.

All answers for the 41 practices, 16 technologies, and 5 indicators were tested for reliability calculating their Cronbach's alpha values. Alpha values of 0.6 or higher were deemed as acceptable [61]. Results for Cronbach's alpha varied from 0.801 to 0.943, indicating high reliability for all questionnaires. We did not perform external validation of LP and Industry 4.0 questions, because those items were extensively validated in previous research. Therefore, the 41 practices were all assumed to belong to one LP implementation dimension. Analogously, we considered the 16 technologies as representative of the Industry 4.0 adoption level.

3.2 Clustering of data

Three clustering of observations were conducted according to different variables: (i) LP practices, (ii) Industry 4.0 technologies, and (iii) operational performance indicators. Hence, we initially utilized Ward's hierarchical method to verify the adequate amount of clusters, denoted by k. Then, we proceeded using the k means clustering method to reorganize responses according to k clusters [62].

For LP implementation, we found two clusters. Further, we performed an analysis of variance (ANOVA), following recommendations from Tortorella and Fettermann [23], to check for differences in clustering variables' means, which indicated significant differences (p values < 0.05) in all 41 variables. Cluster 1 was comprised of 49 respondents whose mean implementation level of LP practices was lower (mean = 2.90), which denoted this cluster as LLP (lower lean production). Cluster 2, consisting of 59 observations, presented a higher average implementation level (mean = 3.93); hence, it was labeled HLP (higher lean production).

When using the adoption level of Industry 4.0 technologies as variables for clustering, a similar approach was performed: ANOVA indicated a significant difference in all 16 Industry 4.0 variables, and clustering procedure resulted in two clusters with significant differences (p value < 0.01) in means. The first cluster, denoted as LTA (lower technology adoption), presented a lower average adoption level (mean = 1.89) and comprised 76 observations. The remaining 32 observations were assigned to the second cluster, which had a higher average adoption level (mean = 3.13) and was labeled as HTA (higher technology adoption).

Finally, the same set of observations was clustered using the improvement level of companies' operational performance as variables. We found two clusters whose differences in means were significant (p values < 0.01) for the five performance indicators through an ANOVA. Cluster 1 corresponded to 49 respondents whose mean improvement level was low (mean = 3.26) and referred as LPI (lower performance improvement), while cluster 2 was formed by 59 respondents that had a higher averages (mean = 4.20) of operational performance improvement. This second cluster was denoted by HPI (higher performance improvement).

3.3 Data analysis

To proceed with the data analysis, we first checked data for normality based upon the Kolmogorov-Smirnov (KS) test and found that the dataset was not normally distributed (p value $<$ 0.05). Hence, suitable non-parametric techniques were identified to analyze this dataset. As dimensions identified at the clustering analysis were deemed as categorical, we applied the chi-squared test with contingency tables and adjusted residuals as technique. For analyzing the contextual factors (considered categorical), a similar approach was used, testing the hypothesis that frequencies in the contingency table are independent [63].

First, it was verified whether the responses' frequency of clusters LLP and HLP was related to the Industry 4.0 adoption (clusters LTA and HTA) in each level of operational performance (LPI and HPI). For that, chi-squared tests were applied, whose adjusted residual values were used to indicate the significance level. The adjusted residual values are the differences between the observed and expected frequencies for a group. Positive values of adjusted residuals mean that observed values are larger than the expected ones, while negative ones mean that observed values are fewer than the expected ones [64]. Significant associations were identified whenever the corresponding adjusted residual value was larger than |1.64|, |1.96|, and |2.58|, indicating a respective significance level of 0.10, 0.05, and 0.01.

An analysis was also undertaken for each of the five studied contextual variables according to Industry 4.0 and LP levels. For companies' LP implementation experience, we classified the dataset into two categories: (i) up to 5 years and (ii) more than 5 years, following Morodin et al. [20] recommendations. Similarly, companies were divided into large- (> 500 employees) and small-sized (≤ 500 employees). For the variable type of ownership, observations were categorized into family- or corporate-owned companies, while with respect to the business operating model, dataset was divided into business-to-business (B2B) or business-to-customer (B2C). Finally, for company's technological intensity, we categorized companies' technological intensity according to their industrial sector [65]. In this sense, two categories of respondents were determined: (i) low and medium-low technological intensity and (ii) high and medium-high technological intensity.

4 Results and discussion

Table 4 displays the results for the Spearman's correlation analysis between each LP practice, denoted by lp_j ($j = 1, \ldots, 41$), and Industry 4.0 technology, labeled as i_k ($k = 1, \ldots, 16$). All significant correlation coefficients were positive, indicating a synergistic relationship between specific pairs of practices and technologies. It is noteworthy that technology i_2 (RFID tag at working units) presented the largest number of significant correlations (25 in total) with LP practices, which suggests a higher pervasiveness of this technology into LP implementation. On the other hand, practice lp_{38} (we dedicate a portion of everyday to planned equipment maintenance-related activities) seems to be the one with the highest potential of integration with Industry 4.0, since it presented significant correlation with 10 out of the 16 technologies.

Table 2 displays the results for the contingency table for combinations between the observation frequencies for Industry 4.0 (LTA and HTA) and LP (LLP and HLP) according to the improvement on operational performance (LPI and HPI). For companies that observed a lower level LP implementation (LLP), adjusted residual values indicated that these companies are more likely to be low adopters of Industry 4.0 (LTA). Moreover, for companies that observed HTA, adjusted residual values indicate that these companies are more likely to be HLP. This relationship is valid for both companies which reached HPI and for companies that reached LPI in the last 3 years. This would suggest that HLP is a facilitating condition for Industry 4.0 adoption while LP adoption is independent from the presence of Industry 4.0 technologies. Further, when a high-performance improvement is observed (HPI), an increase in Industry 4.0 adopters appears, but the adoption level of technologies does not seem to be so relevant. Instead, when performance improvement is high, companies are more likely to be extensively implementing LP practices (HLP).

Three main insights come from the analysis of results: (i) LP implementation combined with Industry 4.0 adoption

Table 2 Chi-squared test among levels of Industry 4.0 technology adoption and LP implementation according to levels of operational performance improvement

Operational performance improvement	Industry 4.0 technology adoption	Lean production practice implementation				Total frequency
		LLP		HLP		
		Frequency	Adjusted residual	Frequency	Adjusted residual	
LPI	LTA	32	3.39***	8	− 3.39***	40
	HTA	2	− 3.39***	7	3.39***	9
	Total frequency	34		15		49
HPI	LTA	12	1.74*	24	− 1.74*	36
	HTA	3	− 1.74*	20	1.74*	23
	Total frequency	15		44		59

*Significant at 10% (adjusted residual > |1.64|); **significant at 5% (adjusted residual > |1.96|); ***significant at 1% (adjusted residual > |2.58|)

leads to high operational performance improvement; (ii) LP is highly adopted in companies where operational performance improvement is high, while there is not a significant association between Industry 4.0 and operational performance improvement; and (iii) adoption of Industry 4.0 is significantly linked to LP implementation, while LP implementation is independent from Industry 4.0 adoption (these results are more prominent when the observed improvement level of operational performance is high).

Our findings suggest that adoption of LP has a stronger positive impact on performance improvement than Industry 4.0 implementation. These results can be justified by two main reasons. First, LP aims at improving the flow of value and minimizing wastes through the active involvement of people towards the establishment of a continuous improvement culture [59, 66]. In other words, LP practices allow process design based on a low-tech principle that fosters simplicity and effectiveness, underpinning robust and continuous achievements in the long run [31, 67]. Thus, it is quite reasonable to observe that processes that underwent a lean implementation may entail some performance improvement disregarding their level of technology adoption. Second, initial reports on LP implementation in EU manufacturers date from mid-1990s [68, 69], which is much earlier than the acknowledgment of Industry 4.0. Therefore, one might expect that EU manufacturers' ability of implementing LP and of exploiting its benefits is much higher than their readiness level of Industry 4.0. The impact of Industry 4.0 on operational performance has been much envisioned [8, 70]; nevertheless, empirical evidence is still scarce due to its still limited dissemination across industries.

Table 3 presents the contingency table and chi-squares for the associations between the implementation levels of LP and Industry 4.0 for each contextual factor under study. Regarding company's LP implementation experience, significant differences in observations frequency were only evidenced for low-experienced companies (≤ 5 years). EU manufacturers that have barely implemented lean practices are also inclined to poorly adopt Industry 4.0 technologies. In turn, companies with higher levels of technology adoption seem to be concurrently implementing LP practices in an extensive way. No significant difference in frequencies was found for high-experienced companies (> 5 years).

For company size, large-sized firms usually imply a higher capital expenditure capacity and more structured managerial processes. In that sense, one might expect that larger manufacturers would be prone to adopt more widely Industry 4.0 technologies [8], such as evidenced with LP practices [18, 71]. Our results confirm such expectation for LP, since HLP frequencies showed that large-sized companies tend to implement LP much more than small-sized companies, and partially confirm for Industry 4.0, as the frequency of HTA is slightly greater in large-sized companies than in small-sized ones. However, the interrelation between LP and Industry 4.0 appears to follow the similar patterns previously observed, indicating that company size may not be a relevant contextual factor for influencing this association in EU manufacturers. Regardless the size, HTA companies are more frequently presenting high implementation levels of LP practices and, when companies are less extensively implementing LP, they are more likely to be categorized as LTA. These findings are somewhat aligned with Tortorella and Fettermann [23], who performed a similar analysis with manufacturers located in a developing economy context. Thus, we evidenced that its findings can also be expanded to manufacturers from a developed economy context, such as EU. Given HLP categorization, large-sized companies are more prone of being HTA than small-sized companies. HLP appears as a necessary condition for Industry 4.0 adoption, but this condition has been more exploited by large-sized companies than small-sized ones. This could be explained by the major availability of financial resources [8].

With respect to the type of ownership, family-owned companies appear to implement LP much less than corporate-owned companies, while regarding adoption of Industry 4.0 technologies, the difference seems negligible. However, the same kind of interrelation between LP and Industry 4.0 is present; i.e., LLP companies are also likely to be LTA, while HTA are more likely to be HLP. Regardless of the level of technology adoption, observations from this type of ownership tend to be extensively implementing LP practices. Such fact can be justified by the increased pressure that corporate companies have in terms of financial and operational performance. As they are stock-based valued, cost reduction and profitability are important drivers for these companies [72, 73]. LP practice implementation entails less waste and, hence, lower cost and higher profitability, which may motivate a more extensive and earlier implementation than family-owned ones. This context may explain why corporate-owned companies are more frequently clustered as HLP independently of the technologies' adoption.

For the business operating model, no significant difference appears between B2B and B2C companies in implementing LP and Industry 4.0. Results show similar frequency likelihoods for the interrelation between both approaches, just as the ones observed for company size. This outcome means that for both B2B and B2C manufacturers, LLP companies imply more frequently LTA, while HTA is quite likely to be widely implementing LP practices. Such finding suggests that, for manufacturers located in EU, delivering value to final consumers or to other businesses does not influence the relationship between LP and Industry 4.0.

Finally, regarding companies' technological intensity, when companies are from industrial sectors whose technological intensities are considered as low or medium-low, no

Table 3 Chi-squared test among levels of Industry 4.0 technology adoption and LP implementation according to contextual factors

Contextual factors		Industry 4.0 technology adoption	Lean Production practices implementation				
			LLP		HLP		Total frequency
			Frequency	Adj. res.	Frequency	Adj. res.	
LP implementation experience	≤ 5 years	LTA	34	3.91***	11	− 3.91***	45
		HTA	4	− 3.91***	14	3.91***	18
		Total frequency	38		25		63
	> 5 years	LTA	9	1.07	22	− 1.07	31
		HTA	2	− 1.07	12	1.07	14
		Total frequency	11		34		45
Company size	≤ 500 employees	LTA	31	2.50**	20	− 2.50**	51
		HTA	4	− 2.50**	12	2.50**	16
		Total frequency	35		32		67
	> 500 employees	LTA	13	3.01***	12	− 3.01***	25
		HTA	1	− 3.01***	15	3.01***	16
		Total frequency	14		27		41
Type of ownership	Family	LTA	32	3.76***	13	− 3.76***	45
		HTA	2	− 3.76***	12	3.76***	14
		Total frequency	34		25		59
	Corporate	LTA	12	1.96**	19	− 1.96**	31
		HTA	3	− 1.96**	15	1.96**	18
		Total frequency	15		34		49
Business operating model	B2B	LTA	20	2.48**	18	− 2.48**	38
		HTA	2	− 2.48**	12	2.48**	14
		Total frequency	22		30		52
	B2C	LTA	24	3.25***	14	− 3.25***	38
		HTA	3	− 3.25***	15	3.25***	18
		Total frequency	27		29		56
Technological intensity	Low and medium-low	LTA	9	1.07	22	− 1.07	31
		HTA	2	− 1.07	12	1.07	14
		Total frequency	11		34		45
	High and medium-high	LTA	34	3.91***	11	− 3.91***	45
		HTA	4	− 3.91***	14	3.91***	18
		Total frequency	38		25		63

*Significant at 10% (adjusted residual > |1.64|); **significant at 5% (adjusted residual > |1.96|); ***significant at 1% (adjusted residual > |2.58|)

significant association was found between LP and Industry 4.0. However, when these companies are categorized as high or medium-high in terms of their technological intensity, results are analogous to the ones previously observed. LTA companies are more frequently assigned as part of the LLP cluster, while HTA ones are more likely to be part of the HLP group. These results reinforce that the implementation of LP practices may serve as a solid foundation on which Industry 4.0 technologies can consistently grow as a management approach.

Overall, our results support the idea of a wide applicability of both approaches, since most of their associations occur at similar extents, regardless of the involved contextual factor. Moreover, when processes are not robustly designed and continuous improvement practices are not established, companies may not be focused on adopting novel technologies either. Based on this, our findings provide evidence that higher levels of Industry 4.0 adoption may be easier to achieve when LP is also highly implemented in the firm.

5 Conclusions

This study aimed at examining the interrelation between LP and Industry 4.0 implementation levels and its impact on operational performance in European manufacturers. Contributions of this research are twofold, impacting both academicians and practitioners.

First, in theoretical terms, this research has provided arguments to empirically analyze the relationship between LP and Industry 4.0 considering various contextual factors. Although previous studies on operations management and LP [18, 56, 74] have evidenced that contingencies must be acknowledged when implementing any particular management practice, our results show that the pervasiveness of the relationship between LP and Industry 4.0 may overcome the effect of some contextual factors. More specifically, our findings indicate that EU manufacturers that aim to adopt higher levels of Industry 4.0 must concurrently implement LP as a way to support process improvements. Further, the outcomes of this study pinpoint that the effects of LP on operational performance improvement still prevail over the impact of Industry 4.0, since all HPI companies seem to claim high levels of LP implementation, regardless of the technologies. This phenomenon is quite reasonable since companies' understanding and implementation maturity with respect to LP are significantly larger than Industry 4.0. It is noteworthy that this result was observed in European manufacturers, the context where Industry 4.0 was originally coined.

From a practical perspective, this study demystifies a few assumptions on the conditions (contextual factors) that might favor the incorporation of Industry 4.0 into classical strategic management approaches, e.g., LP. In fact, our results unveil the association between LP and Industry 4.0 under different contextual factors. By comprehending that Industry 4.0 is positively related to LP, disregarding the context (e.g., company size, business operating model), managers from EU manufacturers can address the implementation of both approaches in a more assertive way. In other words, our research emphasizes that companies that aim at achieving higher levels of Industry 4.0 must have previously implemented a certain level of LP practices. This fact allows companies to fully benefit from the incorporation of technologies into well-designed and robust processes (either operational or strategic). Further, from a socioeconomic point of view, our findings may indicate that the effects of Industry 4.0 are still incipient even in manufacturers from developed economies, and much needs to be investigated in this field.

Some limitations of this research are worth to notice. First, with respect to sample size, larger study samples could allow the investigation of the effects of further contextual factors (e.g., industry sector and supply chain tier level) on the relationship between LP and Industry 4.0. A larger dataset would also increase the degrees of freedom so that the utilization of more sophisticated multivariate data analysis techniques (e.g., structural equation modeling) could be performed. The incorporation of such techniques would enable more robust indications and possibly unveil more insightful results. Additionally, since our study examined the overall effect of the integrated implementation of LP and Industry 4.0 over operational performance improvement, we consolidated both approaches into single dimensions based upon their respective sets of practices and technologies. Such simplification was justified by the fact that companies are still struggling with some of Industry 4.0 technologies and concepts. Hence, to avoid any misconception and biased analysis, we did not perform any specific analysis of this relationship at a "practice-technology" level. However, we acknowledge the importance of deepening the understanding of how this relationship occurs so that practitioners and academics can clearly anticipate any synergistic or concurrent effect. As companies' Industry 4.0 adoption become more mature, future survey-based studies could indicate more assertively how the individual relation between a specific technology and practice could impact performance. Furthermore, since LA has been used to denote the integration of Industry 4.0 into LP, the understanding of specific pairwise relationships could enable the establishment of novel frameworks that would facilitate lean implementation in the fourth industrial revolution era.

Appendix A: Applied questionnaire

This survey is part of an academic study led by operations management researchers from Politecnico di Milano, Italy. Since this is an exploratory study, therefore, there are no right answers for each of the following questions.

It is noteworthy that all responses will be treated anonymously, and confidentiality of data will be kept. Any publication of this material will require authorization beforehand and will only occur with respondents' agreement.

1 – Please, provide the information below:

Number of employees in your company:	( ) Less than 500	( ) More or equal to 500
Type of ownership of your company:	( ) Family-owned	( ) Corporate-owned
Business operating model:	( ) B2B (business-to-business)	
	( ) B2C (business-to-customer)	
LP implementation time length:	( ) ≤ 5 years	( ) > 5 years
Industrial sector of your company:	______________________________	

2. *Please, indicate below the agreement level with the following statements based upon your company's current status:*

Lean production	Fully disagree			Fully agree	
	1	2	3	4	5
We frequently are in close contact with our suppliers					
We give our suppliers feedback on quality and delivery performance					
We strive to establish long-term relationship with our suppliers					
Suppliers are directly involved in the new product development process					
Our key suppliers deliver to plant on JIT basis					
We have a formal supplier certification program					
Our suppliers are contractually committed to annual cost reductions					
Our key suppliers are located in close proximity to our plants					
We have corporate level communication on important issues with key suppliers					
We take active steps to reduce the number of suppliers in each category					
Our key suppliers manage our inventory					
We evaluate suppliers on the basis of total cost and not per unit price					
We frequently are in close contact with our customers					
Our customers give us feedback on quality and delivery performance					
Our customers are actively involved in current and future product offerings					
Our customers are directly involved in current and future product offerings					
Our customers frequently share current and future demand information with marketing department					
Production is pulled by the shipment of finished goods					
Production at stations is pulled by the current demand of the next station					
We use a pull production system					
We use *kanban*, squares, or containers of signals for production control					
Products are classified into groups with similar processing requirements					
Products are classified into groups with similar routing requirements					
Equipment is grouped to produce a continuous flow of families of products					
Families of products determine our factory layout					
Our employees practice setups to reduce the time required					
We are working to lower setup times in our plant					
We have low set up times of equipment in our plant					
Large number of equipment/processes on shop floor are currently under SPC					
Extensive use of statistical techniques to reduce process variance					
Charts showing defect rates are used as tools on the shop floor					
We use fishbone type diagrams to identify causes of quality problems					
We conduct process capability studies before product launch					
Shop floor employees are key to problem solving teams					
Shop floor employees drive suggestion programs					
Shop floor employees lead product/process improvement efforts					
Shop floor employees undergo cross functional training					
We dedicate a portion of everyday to planned equipment maintenance related activities					
We maintain all our equipment regularly					
We maintain excellent records of all equipment maintenance related activities					
We post equipment maintenance records on shop floor for active sharing with employees					

3. *Please, indicate below the adoption level of the following digital technologies in your company:*

Digital technologies	Not used		Fully adopted		
	1	2	3	4	5
Robotic stations on automated production line					
RFID tag at working units					
Real-time scanning by smartphone or tablet application					
Machines with digital interfaces and sensors					
Augmented reality					
Cloud computing system					
Collaboration with suppliers/customers through real-time data sharing					
Predictive maintenance through real-time monitoring					
Artificial intelligence and machine learning algorithms					
Production process autonomous management					
Digital automation without sensors					
Sensors for product/operating conditions identification					
Integrated engineering systems					
Additive manufacturing, rapid prototyping or 3D printing					
Big data					
Internet of Things					

4. *Please, indicate the improvement level of the following operational performance indicators observed in your company during the last three years:*

Operational performance indicators	Worsened significantly Improved significantly				
	1	2	3	4	5
Productivity					
Delivery service level					
Inventory level					
Workplace safety (accidents)					
Quality (scrap and rework)					

Appendix B: Spearman's correlation between LP practices and I4.0 technologies

Table 4 Spearman's correlation between LP practices and I4.0 technologies

	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}	i_{16}
lp_1		0.223**			0.218**			0.187*						0.175*		
lp_2		0.204**		0.195**	0.251**		0.224**	0.248**				0.169*				
lp_3				0.170*			0.237**	0.260***							0.188*	
lp_4		0.233**		0.247**		0.224**	0.248**		0.188*				0.205**			
lp_5				0.281***		0.202**	0.178*									0.192*
lp_6		0.235**		0.202**	0.164*		0.399***				0.221**					
lp_7				0.178*								0.171*				0.235**
lp_8							0.292***				0.323***		0.201**			0.169*
lp_9		0.190*					0.220**	0.219**								0.256**
lp_{10}			0.166*									0.182*			0.168*	
lp_{11}		0.181*	0.216**	0.208**							0.411***		0.258**			
lp_{12}							0.193*							0.189*		
lp_{13}		0.211**				0.277***	0.188*		0.171*					0.311***	0.245**	
lp_{14}											0.179*	0.211**				0.169*
lp_{15}							0.250**	0.199**						0.284***		
lp_{16}								0.174*					0.211**			
lp_{17}		0.296***	0.245**	0.251**			0.322***	0.276***				0.194*				
lp_{18}						0.235**		0.191*							0.199*	0.222**
lp_{19}						0.281***	0.256***					0.166*		0.175*		
lp_{20}						0.172*	0.218**				0.221**	0.240**				
lp_{21}					0.190*	0.175*	0.224**	0.201**				0.280***	0.304***			
lp_{22}	0.225**	0.190*		0.176*			0.167*	0.164*						0.188*	0.183*	
lp_{23}				0.188*				0.167*	0.176*							0.351***
lp_{24}		0.265**	0.196**	0.333***		0.167*		0.280***	0.268***							0.265**
lp_{25}												0.233**	0.193*			
lp_{26}		0.259***	0.183*	0.304***								0.211**				
lp_{27}		0.248**		0.351***				0.183*			0.177*		0.195**			
lp_{28}				0.168*					0.228**				0.245**			
lp_{29}		0.239**	0.227**	0.332***	0.264***			0.205**				0.272**				
lp_{30}	0.210**	0.370***	0.378***	0.468***	0.245**	0.270***		0.335***						0.281***	0.166*	
lp_{31}		0.380***	0.299***	0.374***	0.281***	0.186*	0.309***	0.337***			0.297***					0.218**
lp_{32}		0.195**	0.182*	0.275***						0.256***	0.168*		0.182*			

Table 4 (continued)

	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}	i_{16}
lp_{33}		0.347***		0.297***	0.280***	0.262***		0.180*					0.272***		0.205**	
lp_{34}		0.282***	0.194*	0.343***	0.205**	0.212**		0.272***			0.225**			0.210**	0.194*	
lp_{35}		0.252**		0.264***	0.176*			0.177*			0.176*					
lp_{36}		0.265***		0.216**	0.224**	0.214**	0.215**	0.202**			0.214**	0.175*	0.191*			
lp_{37}		0.250**	0.249**	0.245**	,255**	0.185*	0.269**	0.421***	0.174*					0.239**		
lp_{38}	0.193*	0.419***	0.219**	0.323***	0.230**	0.168*	0.260***	0.171*							0.186*	0.193*
lp_{39}		0.363***	0.207**	0.260***	0.196**	0.285***		0.216**	0.253**	0.229**						0.380***
lp_{40}		0.390***	0.175*	0.316***	0.210**		0.239**	0.273***		0.240**					0.225**	
lp_{41}	0.186*	0.216**	0.224**	0.261***								0.175*	0.191*			

*Significant at 10%; **significant at 5%; ***significant at 1%

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