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Exploring lean manufacturing practices' influence on process innovation performance

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ABSTRACT

Little is known about the effects of lean manufacturing practices on the process innovation performance of manufacturing organisations. This research aims to fill this gap and explore the aforementioned interdependency. A research framework consisting of 22 measurement scales and three pairs of hypotheses was developed based on an extensive literature review. A large-scale self-administered questionnaire was distributed among appropriately selected industrial experts. Datasets obtained from 340 usable responses were analysed through confirmatory factor analysis, descriptive statistics, correlations, and multiple linear regression models. The findings suggest that both technical and human lean practices have a moderate to strong positive impact on the input and occurrence of incremental and radical process innovation in manufacturing organisations. In turn, as an output of process innovation, this appears to enhance companies' operational performance. Thereby, the results dispel the scholarly and managerial misconception that LM and innovation are difficult to coexist.

1. Introduction

Over the last 30 years, lean manufacturing (LM) has provided some of the most popular and effective practices and tools for striving towards operational excellence (Albliwi, Antony, & Lim, 2015). In essence, LM aims to eliminate any non-value-adding activities through continuous incremental improvements (Abolhassani, Layfield, & Gopalakrishnan, 2016).

Global megatrends have accelerated the pace of technological developments, increasing the importance of dynamic operations (Westkämper, 2014). In this environment, merely optimising the exploitation of innovation is not enough. Companies are challenged to enhance their explorative innovation capabilities to ensure sustainable competitive advantages (Chen & Huang, 2009; Kafetzopoulos, Gotzamani, & Gkana, 2015). In addition to managing existing products and services, they must incrementally and radically innovate in technology and processes to outpace global competition (Westkämper, 2014).

On one hand, exploitation and exploration seem contradictory (Berente & Lee, 2014; Jones & Linderman, 2014; Pakdil & Leonard, 2017). By principle, standardised lean environments appear to be the opposite of increased worktime flexibility and colourful creativity rooms. Similarly, structured and streamlined workflows associated with LM seemingly contradict the need of freedom to innovate. Pakdil and Leonard (2017) outline a paradox of LM: while employees are encouraged to continuously innovate autonomously, guidelines and work regulations provide strict rules for their operations. Spear and Bowen (1999) also describe the Toyota Production system as a paradox between rigid processes and flexible responsiveness. Jones and Linderman (2014) call this a trade-off between innovation and efficiency of manufacturing plants. However, LM is centred on improvement (Jasti & Kodali, 2015), and increasing innovativeness is occasionally presented as an important mechanism for LM (Lyons, Vidamour, Jain, & Sutherland, 2013). In addition, various human resource (HR) oriented LM practices (e.g. diverse training, teamwork, and flatter hierarchies) (Olivella, Cuatrecasas, & Gavilan, 2008) are often listed among general attributes of innovation fostering environments (Dul & Ceylan, 2014; Fiates, Fiates, Serra, & Ferreira, 2010). Together, the outlined contradictions raise the question as to whether, and in which way, the implementation of LM affects the ability of manufacturing organisations to generate process innovations.

Scholars have addressed this question from a variety of different viewpoints. Table 1 presents an overview of research regarding the effects of LM on (process) innovation. Nevertheless, in most of these studies, LM is only partly covered in overarching relation to (1) process management or improvement initiatives (Berente & Lee, 2014; Jones &

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Table 1
Previous research on the impact of LM practices on innovation performance.

Perspective on lean	Author(s)	Coverage of types of innovation (product and/or process)	Research methodology	Subject of investigation
Lean as process management/improvement initiative	Jones and Linderman (2014)	Focus on product innovation	Quantiative (Survey)	Effects of process management initiatives (including lean) on innovation and OP
	Berente and Lee (2014)	Product & process innovation	Theory-based	Impact of process improvement efforts (including lean) on organisational innovativeness
Lean six sigma	Byrne et al. (2007)	Not clearly distinguished	Theory-based	Lean six sigma as an approach to foster innovation
	Johnstone et al. (2011)	Not central to the investigations	Theory-based	Comparison of lean six sigma, creativity, and innovation in general
	Antony et al. (2016)	Product & process innovation	Qualitative (Interviews)	Interdependencies between lean six sigma and product, service, and process innovation
Lean design and lean supply chain management	Chen and Taylor (2012)	Not clearly distinguished	Quantitiaitve (Survey)	Impact of lean design on radical innovation capability
	Taylor (2010)	Not clearly distinguished	Quantitative (Survey)	Effects of lean design and lean supply chain management on organisational responsiveness to innovations
Lean enterprise	Chen et al. (2010)	Not central to the investigations	Theory-based	Advantages and disadvantages of lean manufacturing management on various organisational aspects
General lean attributes, principles, and aims	Melnyk (2007)	Not clearly distinguished	Theory-based	Impacts of lean principles and general attributes on creativity and innovation
	Browning and Sanders (2012)	Not central to the investigations	Theory-based	Comparison of lean principles with novel and complex (innovative) paradigms
	Weber (2014)	Product & process innovation	Qualitative (Interviews)	Impacts of lean in general on innovation performance and innovation processes
HLPs and lean work organisation	Mehri (2006)	Not central to the investigations	Qualitative (Case study)	Effects of lean principles and practices on workers
	Arundel et al. (2007)	Not clearly distinguished	Quantiative (Database)	Work organisations (including lean) and innovation modes of european countries and their companies
Set of practices with focus on TLPs	Borrèl (2013)	Not clearly distinguished	Qualitative (Questionaire & Interviews)	Effects of lean management on the tension between exploration and exploitation
	Siemerink (2014)	Focus on product innovation	Qualitative (Questionaire & Interviews)	Impact of lean management on organisational structure and the organisation of innovation in SMEs
TLPs & HLPs	Lewis (2000)	Focus on product innovation	Qualitative (Case studies)	Interdependencies between lean manufacturing and sustainable competitive advantage
	Chen and Taylor (2009)	Not clearly distinguished	Theory-based	Impact of lean management on innovation capability
TLPs & HLPs	Present Work	Process innovation	Quantitative (Survey)	The Impact of lean practices on the process innovation performance of manufacturing organisations

Linderman, 2014), (2) lean six sigma (Antony, Setijono, & Dahlgaard, 2016; Byrne, Lubowe, & Blitz, 2007; Johnstone, Pairaudeau, & Pettersson, 2011), (3) lean design (Chen & Taylor, 2012) and lean supply chain management (Taylor, 2010), (4) lean enterprise (Chen, Lindeke, & Wyrick, 2010), (5) general attributes, principles, and aims of lean (Browning & Sanders, 2012; Melnyk, 2007; Weber, 2014), (6) human lean practices (HLPs) and lean work organisation (Arundel, Lorenz, Lundvall, & Valeyre, 2007; Mehri, 2006), or (7) primarily technical lean practices (TLPs). Although a few authors combine TLPs with HLPs (e.g. Chen & Taylor, 2009; Lewis, 2000), none of the studies capture a truly holistic and structured overview of LM.

Moreover, LM has a more direct relation to process innovation than product innovation (Schultz & Strømmen, 2015; Weber, 2014). However, in relevant literature, innovation is (1) approached including both product and process innovation or more (Antony et al., 2016; Berente & Lee, 2014; Weber, 2014), (2) not (clearly) distinguished between product and process innovation (Arundel et al., 2007; Borrèl, 2013; Byrne et al., 2007; Chen & Taylor, 2009; Chen & Taylor, 2012; Melnyk, 2007; Taylor, 2010), (3) examined with focus on product innovation (Jones & Linderman, 2014; Lewis, 2000; Siemerink, 2014), or (4) not central to the investigations (Chen et al., 2010; Mehri, 2006). Furthermore, some studies compare lean and innovation rather than investigating causal interdependencies (Browning & Sanders, 2012; Johnstone et al., 2011). Although the aforementioned studies rather explore the relationship between LM and processes than products, none of them exclusively examines the impacts of lean practices on comprehensively measured process innovation performance.

Furthermore, only a few otherwise limited studies use large scale quantitative-based approaches (Arundel et al., 2007; Chen & Taylor, 2012; Jones & Linderman, 2014; Taylor, 2010). The majority of studies apply theory-based (Berente & Lee, 2014; Browning & Sanders, 2012; Byrne et al., 2007; Chen et al., 2010; Chen & Taylor, 2009; Johnstone et al., 2011; Melnyk, 2007) or qualitative research methodologies partly mixed with small scale questionnaires (Antony et al., 2016; Borrèl, 2013; Lewis, 2000; Mehri, 2006; Siemerink, 2014; Weber, 2014). This entails inherent limitations, since theory-based investigations lack practical significance, and qualitative research is dominated by subjective perceptions of specific cases (Ayhan, Öztemel, Aydin, & Yue, 2013). For LM as a world-wide phenomenon, robust quantitative research offers a more solid alternative to provide an initial overview, generalise significant inferences, and guide further and more detailed research. For these reasons, the overall effect of LM on process innovation and the operational performance (OP) of manufacturing organisations may still be considered inconclusive.

Therefore, to complement and expand the limited body of knowledge on the effects that LM has on process innovation and their link to OP, this paper addresses the following research question:

What is the effect of technical and human LM practices on incremental and radical process innovation, and how do these mediate LM and the OP of manufacturing firms?

The rest of the paper is structured as follows: Section 2 presents the literature review and hypotheses; Section 3 introduces the research methodology; the analysis and interpretation of results are included in Section 4; lastly, Section 5 provides derived conclusions, limitations and future research directions.

2. Literature review

2.1. General relationship between LM and innovation

Schroeder, Scudder, and Elm (1989) suggest management approaches such as just-in-time (JIT), zero defects, and quality circles as indicators for innovativeness. Similarly, Armbruster, Bikfalvi, Kinkel, and Lay (2008) consider some LM tools as organisational innovations (e.g. manufacturing cells, JIT, Kanban, cross-functional teams, decentralisation, or flattened hierarchies). Berente and Lee (2014) claim that process improvement techniques, including lean practices, are a form of innovation. Consequently, as Alpenberg and Scarbrough (2016) suggest that LM itself can be perceived as an innovation.

If considered as two separate entities, lean and innovation reveal fundamentally different characteristics. Reinertsen and Schaeffer (2005) point out the main differences between research and development (R&D) and LM: innovation requires risk-taking and primarily deals with information instead of physical items. Browning and Sanders (2012) add that lean is typically applied in repetitive, stable, and certain environments, whereas Mehta and Shah (2005) note that it aims for low variability. In contrast, innovation is described as novel, complex, and thus dynamic and often unfamiliar (Browning & Sanders, 2012). Biazzo, Panizzolo, and De Crescenzo (2016) emphasise that lean is focused on incremental innovation as opposed to more radical change. Thus, it is generally concluded that lean principles cannot be adopted unchanged to R&D and innovation management.

However, several scholars have adapted lean principles to propose so-called lean innovation models. Srinivasan (2010) argues that lean and innovation can be complementary, and translates lean principles into innovation management objectives. Other models focus on stakeholder value orientation for incremental innovation, and aim to increase radical innovation output with limited resources (Bicen & Johnson, 2015). Advocating lean innovation rather than scientifically investigating interdependencies in a robust manner, Sehested and Sonnenberg (2011) relativise critique on the application of lean practices to innovation by distinguishing lean innovation as an individual management concept.

Despite the inflationary multitude of research and frameworks regarding lean innovation (Bicen & Johnson, 2015; Sehested & Sonnenberg, 2011), the impact of conventional LM practices on process innovation performance has not yet been subject to thorough investigation (see Section 1). LM tools as well as process innovation performance have neither been studied in this specific combination nor individually with a comprehensive causal intention. To approach this gap, the existing related literature is used in the following section to derive inferences about causal effects of LM on process innovation and OP.

2.2. Formulation of hypotheses and development of research framework

2.2.1. Technical lean practices (TLPs) and process innovation

Kim, Kumar, and Kumar (2012) find that the application of process techniques in quality management practices has positive effects on incremental and radical product, process, and administrative innovation. They note that improvements are far more likely to be achieved through simultaneous implementation of multiple quality management initiatives, which is most often the case in LM. Everett and Sohal (1991) suggest that the use of Andons increases workers' motivation and enhances mental processes that exist in play. This can be expected to lead to new ideas for incremental, and possibly even radical innovation.

Borrèl (2013) concludes that the application of lean principles and TLPs does not necessarily harm small and medium sized enterprises' (SMEs) explorative innovativeness, as they can employ balanced innovation strategies after initial exploitation. Siemerink (2014) proposes that possible influences of lean principles and TLPs on organisational structure in SMEs are also non-significant regarding incremental and radical innovation. Jones and Linderman (2014) demonstrate a controversy in the literature about the question as to whether process management (including lean initiatives) positively or negatively affects innovation performance. They conclude that related practices can be tailored to avoid losses of innovativeness. Berente and Lee (2014) argue that the objective of process improvement (including lean initiatives) is to increase efficiency, standardisation, and uniformity, which directly increases innovation performance. Furthermore, they claim it improves capacity, knowledge, and management support, in turn also positively affecting innovation performance.

However, Lewis' (2000) empirical work demonstrates that LM can decrease organisations' long-term flexibility. Browning and Heath (2009) discuss lean's drawbacks in novel and complex surroundings, and propose complementing LM with other innovation systems. Similarly, Melnyk (2007) demonstrates differences between lean principles and innovative environments. He emphasises that lean's slack reduction harms innovative power, and claims that both systems must be separated to coexist. Chen et al. (2010) emphasise that focusing on waste reduction and non-value-adding activities draws companies' attention to short-term profitability. In turn, they argue, organisations might neglect non-productive exploration that could yield radical innovation and thus be a worthwhile investment. Nevertheless, Lewis (2000), Borrèl (2013), and Weber (2014) claim that resources freed up by LM can be used to support investments in sustainable competitive advantage.

Chen and Taylor (2009) develop a framework to investigate the influences of LM on innovation performance. They highlight differences in both paradigms and propose five negative effects to guide future research. However, similar to Arundel et al. (2007), they expect LM to have a positive impact on incremental innovation performance, explicitly regarding processes. This is aligned with Imai's (1986) indications of strong similarities between CI and incremental innovation.

Multiple innovation and creativity-focused studies allow similar inferences. According to Damanpour (1991), standardisation, which is the aim of several LM practices, has negative impacts on innovation capability. This is because it restricts workers' engagement (Olivella et al., 2008), and thus their independent thought and action. Especially, TLPs entail high levels of formalisation and standardised regulations. Similarly, Weber (2014) emphasises that the reduction or elimination of slack, experimental waste, risks, and variability, which are normally the result of TLPs' deployment, can have negative effects on innovation as they are essential to innovate. Lean principles arguably promote autonomy, but employees are expected and sometimes pressured to constantly improve and innovate (Mehri, 2006). Although certain forms of intellectual pressure can enhance creativity and thus innovation, workload pressure is commonly found to entail negative effects (Olivella et al., 2008) and might lead to adopting the first apparent solution.

Altogether, while TLPs presumably enhance incremental innovation performance, most scholars indicate negative impacts of TLPs on radical process innovation. Therefore, the inconclusive evidence and contradictions regarding the effect of TLPs on innovation performance exposed through the previous discussion call for further research regarding the following hypotheses:

H1a. TLPs increase incremental process innovation (IPI) performance

H1b. TLPs decrease radical process innovation (RPI) performance

2.2.2. Human lean practices (HLPs) and process innovation

Some authors suggest negative effects of HLPs on innovation performance. Arundel et al. (2007) argue that the implementation of lean practices does not often align with ideal-typical theory, but is adapted to local culture and may overlap with other forms of work organisation such as Taylorism. This can negatively affect companies' innovativeness and distort research findings. Parker (2003) suggests that some (human) lean practices lead to negative human-related consequences (i.e. less organisational commitment, decreased self-efficacy, and job depression). Cooper (1998) acknowledges that centralisation is beneficial to the speed in which organisations adopt innovations. Therefore, the decentralisation of power within LM environments might decrease companies' flexibility towards radical changes. Mehta and Shah (2005) highlight several negative impacts of lean management on employees, including a lack of freedom, reduction in discretion, and low task identity. Bouville and Alis (2014) reveal further negative effects of some lean work organisation practices on employees' attitudes and health. They indicate a restriction of creative power which most likely decreases innovation performance.

In contrast, various scholars agree on positive effects of HLPs on workforces' innovative potential. Lyons et al. (2013) incorporate creative involvement of employees as a key lean concept aiming to increase incremental improvement and innovation. Dul and Ceylan's (2014) finding that creativity support has a positive influence on product innovation performance may be transferrable to process innovation. Reinertsen and Schaeffer (2005) indicate that some main lean management attributes can increase innovation performance. Apart from some negative influences, Weber (2014) argues that HLPs such as continuous training, collaboration, and engagement create an innovation supporting environment.

Furthermore, several authors have revealed positive impacts of lean six sigma on innovation. Byrne et al. (2007) report lean six sigma companies that increased their innovation performance by creating an expectation towards innovation. Johnstone et al. (2011) demonstrate positive overlaps of lean sigma with innovation for the pharmaceutical sector, but argue that LM does not inherently enhance or contradict innovation. It is the appropriate journey towards leanness that creates an environment assisting with problem-solving techniques, stimulating new ideas, and giving employees the autonomy to contribute to innovation (Johnstone et al., 2011). Antony et al. (2016) conclude that lean six sigma enhances innovation capability, especially IPI. They define an extensive list of innovation fostering quality management practices, many of which are HR-related.

Additionally, the literature also reveals various HR-related practices that are common in LM and enhance innovation (Damanpour, 1991; Fiates et al., 2010). These include, among others, diversity, training, interdivisional communication, and flattened hierarchies, and job complexity (significance, autonomy, skill, variety, etc.).

The insights from the discussion above permit establishing some conclusions about the relationship between HLPs and process innovation. In this line, skill development and training, especially building multi-functional workforce, presumably enable employees to think outside the boundaries of their usual work. Teamwork and collaboration are expected to ignite synergies regarding the open communication and diffusion of ideas and innovative problem-solving approaches. Close supplier coordination enlarges the input into the innovation funnel (Tomlinson & Fai, 2013), especially driving process innovation (Antonelli & Fassio, 2015). Workforce engagement may enable employees to more easily implement incremental innovation, and might also encourage them to express propositions for radical innovation. Management and leadership techniques, decentralisation of power, increased management support, and performance feedback may potentially simplify and thus accelerate innovation processes. Only structure and standardisation seem to limit innovation-related performance (Chen & Taylor, 2009; Damanpour, 1991). As Weber (2014) suggests, the inconsistencies found in the literature advocates the need for future research of the following hypotheses:

H2a. HLPs increase incremental process innovation (IPI) performance

H2b. HLPs increase radical process innovation (RPI) performance

2.2.3. Process innovation and operational performance (OP)

Various scholars consider OP as an innovation output, and use it to measure process innovation performance (Ayhan et al., 2013; Kirner, Kinkel, & Jaeger, 2009; Trantopoulos, Von Krogh, Wallin, & Woerter, 2017). However, only few studies directly investigate their relationship. Thus, the present work additionally disentangles cause (i.e. process innovation input/efforts and occurrence/intensity) from effects (i.e. OP) to verify mediating impacts.

Schroeder et al. (1989) expect new ideas or production process innovation to lead to improvements in manufacturing performance. They suggest these improvements can be measured in (relative) unit cost, quality, productivity/employee, service levels, inventory turnover, and flexibility. Huergo and Jaumandreu (2004) report a positive effect of process innovation on productivity growth. Gunday, Ulusoy, Kilic, and Alpkan (2011) find evidence of positive influences of general innovation performance (i.e. organisational, product, process, and marketing innovation) on operational manufacturing performance (i.e. flexibility, speed, cost, and quality). Ayhan et al. (2013) claim that process innovation adds value to companies by improving labour utilisation, balancing production sequences, increasing speed, and lowering manufacturing costs. Lee, Zhou, and Hsu (2015) conclude that process innovation decreases flow and lead time and reduces raw material, work in progress (WIP) and finished goods inventory. They also mention improvements in product and process quality as well as cost reductions. Other scholars who argue and/or demonstrate the positive effect of process innovation on OP include Trantopoulos et al. (2017) and Kafetzopoulos et al. (2015). Since none of the aforementioned authors differentiate the outcomes of IPI and RPI performance, it is assumed that both affect OP in a similar way. Therefore, the two related hypotheses were formulated as follows:

H3a. Incremental process innovation (IPI) increases OP

H3b. Radical process (RPI) increases OP

2.2.4. Research framework

Fig. 1 illustrates the theoretical research framework, including the previously formulated hypotheses. Its five dimensions TLPs, HLPs, IPI, RPI, and OP (shown as ovals) were conceptualised through several corresponding items (listed in rectangles), which were interconnected through the developed hypotheses (indicated with arrows). In general, the model illustrates the hypothesised antecedents and consequences of the mediating effect of process innovation input (i.e. efforts) and occurrence (i.e. intensity) between LM and OP. Thereby, it constitutes the foundation for the empirical study.

3. Research methodology

3.1. Questionnaire survey design

Natural ontological deliberations involved in a research of this type may incorporate a degree of subjectivity. To balance subjective variability, and because of the study's positivistic epistemological nature, a large-scale quantitative approach was followed. In line, data was collected by means of a remote and self-administered survey. Firstly, the impersonal questionnaire strategy ensures a separation of researcher and research subject, and eliminates interviewer biases that might distort results (Bryman, 2016). Secondly, the study aimed to generate quantifiable data from large scale samples. Surveys, especially self-administered questionnaires, are efficient (i.e. cheap, quick, and convenient), offer anonymity for respondents, and very importantly, produce the aimed for generalisable results (Bryman, 2016; Forza, 2016). Thirdly, data was intended to be statistically analysable for reliable inferential conclusions about the interdependencies between the research framework's dimensions and items.

The previously developed research framework (see Fig. 1) was transformed into a linear structure with an introduction and three main sections (see Fig. 2). In favour of structure and clarity, the question sequence was determined to be the same for all participants. Since the study was carried out online and globally, as few as possible, close-

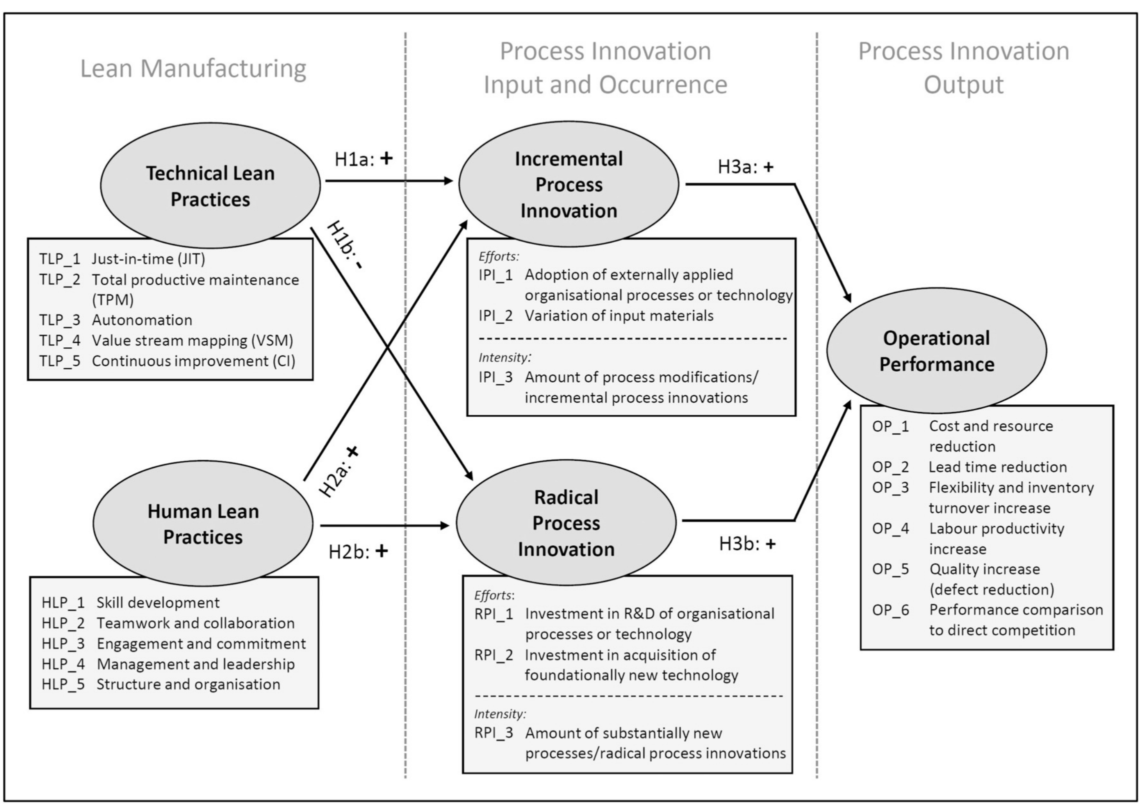

Fig. 1. Holistic research framework.

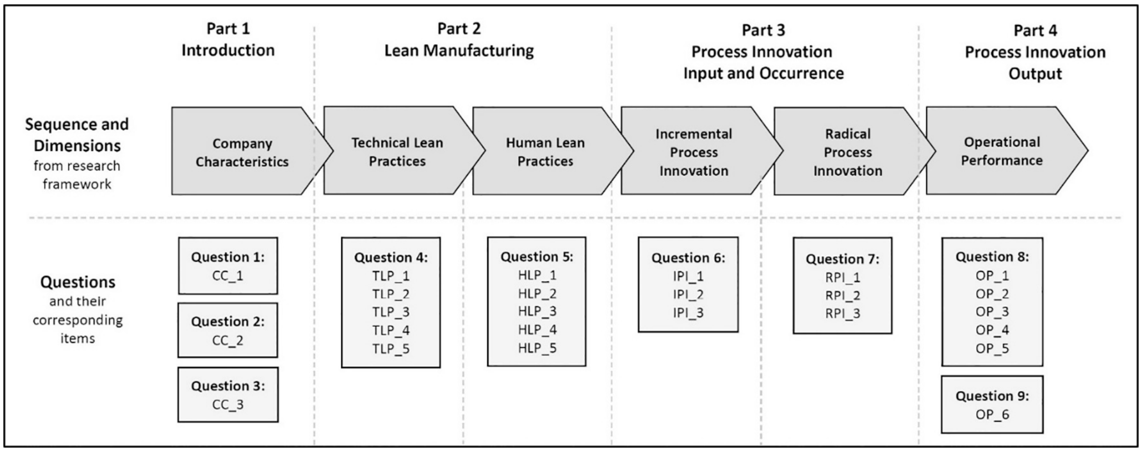

Fig. 2. Questionnaire structure and sequence.

ended, and non-suggestive questions were formulated in a particularly concise and simple language (Bryman, 2016; Hair, Celsi, Money, Samouel, & Page, 2016). The survey was digitalised using the software *Qualtrics*.

Table 2 summarises all questions and the reasons for their inclusion. To reflect on the validity of inferences, three introductory questions characterised the sample companies regarding their size, sector, and region. The following six questions in the three main parts of the questionnaire measured all 22 items from the five research framework's dimensions, namely TLPs, HLPs, IPI, RPI, and OP. Their inclusion was inherently justified by their presence in the research framework, because the aim of the questionnaire was to test the framework's hypotheses. A five-point Likert-type scale was chosen to strike a balance between complexity for respondents and accuracy for analysis (Forza, 2016; Hair et al., 2016). Construct variables were defined as the sum of all respective items.

3.2. Questionnaire validation – small-scale pilot study

Pilot studies are essential to ensure validity when questionnaires are

Table 2
Overview of questions and reasons for their inclusion.

Questions and Sub-questions		Theoretical Foundation and Reason for Inclusion
Q1: Please indicate the size of your organisation. Q2: Where does your organisation mainly manufacture and operate? Q3: Please indicate the manufacturing sector of your organisation.		**Sample characterisation:** Required to reflect biases and inferential limitations by identifying disproportional representations
Q4: To which extent has your organisation implemented…	… just-in-time? … total productive maintenance? … autonomation? … value stream mapping? … continuous improvement?	Measures items **TLPs 1–5** of the research framework: Required to test H1a & H1b
Q5: In the course of lean practices, to which extent does your organisation specifically foster…	… skill development? … teamwork and collaboration? … engagement and commitment? … management and leadership? … structure and organisation?	Measures items **HLPs 1–5** of the research framework: Required to test H2a & H2b
Q6: In the past three years, how often has your organisation…	… adopted processes or process technology form other companies? … varied input materials of manufacturing processes? … modified, redesigned, imitated, improved, or incrementally innovated existing processes and their technology?	Measures items **IPI 1–3** of the research framework: Required to test H1a, H2a, and H3a
Q7: In the past three years, to which extent has your organisation…	… invested in Research & Development specifically dedicated to process improvement or process innovation? …invested in purchasing new technology for manufacturing processes? …implemented entirely new processes or radical process innovations?	Measures items **RPI 1–3** of the research framework: Required to test H1b, H2b, and H3b
Q8: Considering the manufacturing and logistics performance of your organisation over the past three years, how have the following indicators improved?	Unit cost, energy consumption & material requirement Production time, delivery time, and service levels Flexibility and inventory turnover Labour productivity and utilisation Output conformance quality, scrap, and rework rates	Measures items **OP 1–6** of the research framework: Required to test H3a & H3b
Q9: How has the overall operational competitiveness of your organisation improved over the past three years relative to the sector average?		

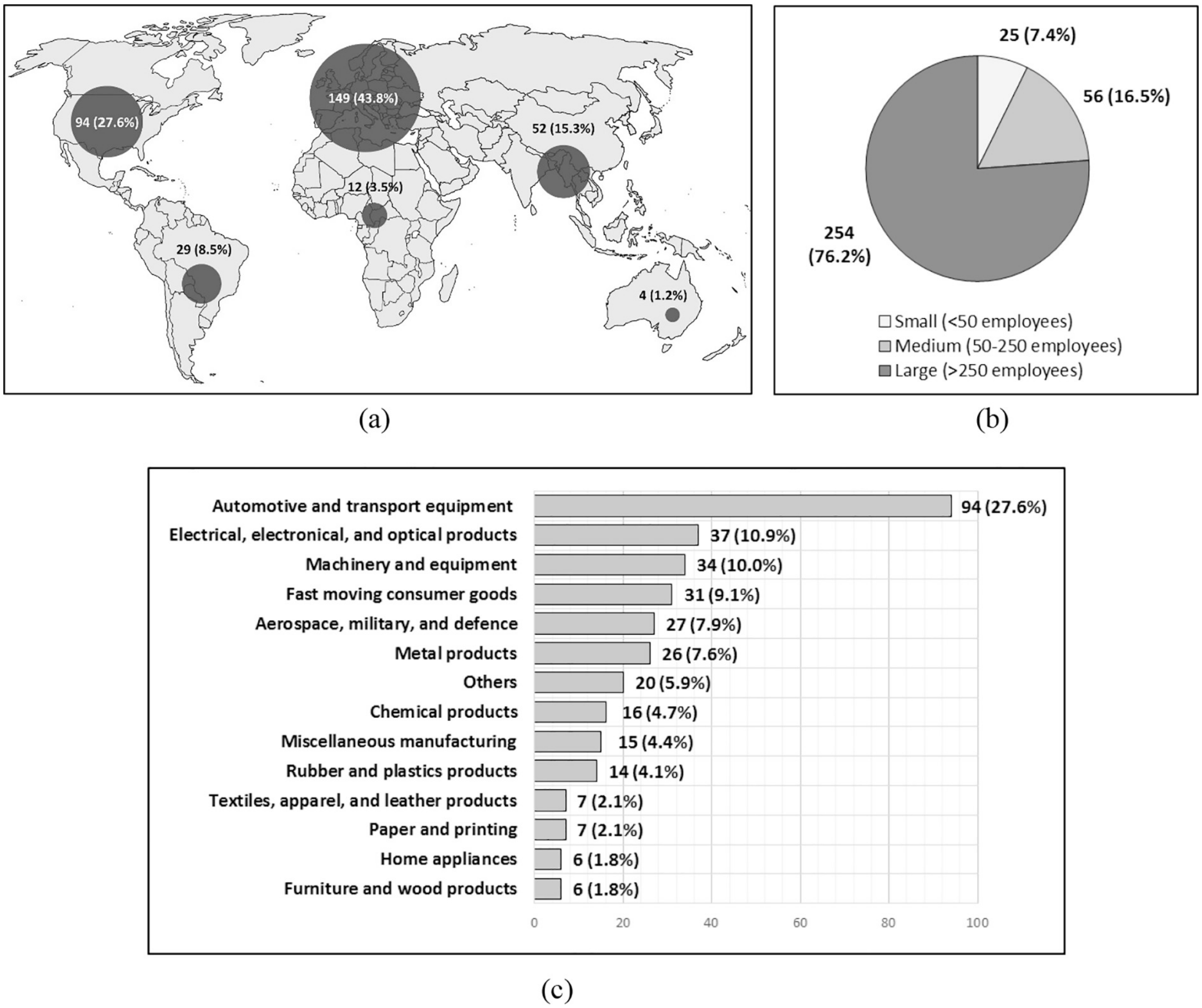

Fig. 3. Sample characteristics – companies' (a) location, (b) size, and (c) manufacturing sector.

self-administered or contain self-developed scales (Bryman, 2016; Hair et al., 2016). A small-scale qualitative validation study was preferred over a quantitative pilot run to obtain comprehensive feedback and preserve candidates for the main data collection. Four academics and five industrialists in the field of operations management revised the questionnaire. Besides a simplification of the scale for companies' sector, the experts' comments only led to minor adjustments of appearance, wording, and spelling.

3.3. Questionnaire survey distribution

The central research question did not limit the target population and sample to certain company characteristics like size, sector, or region. For this unknown but presumably large population, the sample size does not directly depend on the population, but for pragmatic reasons can be estimated based on best practice in related literature (Hair et al., 2016). The reviewed studies imply a requirement of at least 150 participants. However, considering Jasti and Kodali's (2015) call for larger and more global samples in LM research and the study's objective of obtaining generalisable results, it was aimed to significantly exceed this number. Due to the unknown population size, random probability sampling was not possible (Saunders, Lewis, & Thornhill, 2016). The sample was self-selected as randomly as possible among potential candidates matching the target population criteria (i.e. knowledgeable industrial experts from multiple company sizes, sectors, and regions). Participants included lean six sigma belt holders, production managers, team leaders, department managers, and executives working in manufacturing organisations.

The questionnaire was sent to about 1000 selected target group individuals and posted in around 20 LM-related professional social media platforms. A total of 397 responses was generated, containing 346 fully complete datasets. After eliminating six obviously biased and/or unengaged records (evidenced by zero variance), 340 data points were used to conduct the analyses presented in the subsequent sections. The validation of the research framework and its constructs is presented in Appendix A1.

4. Results, analysis, and discussion

4.1. Survey participants

Fig. 3 presents the (a) geographical distribution, (b) size, and (c) manufacturing sector of the respondents' organisations.

Table 3
H1a: TLPs-IPI (a) Spearman correlations and (b) MLR model/H1b: TLPs-RPI (c) Spearman correlations and (d) MLR model.

(a)

	Incremental Process Innovation	Process adoption	Input material variation	Incremental process innovation
Technical lean practices	**0.462****	0.352**	0.342**	0.414**
Just-in-time	0.329**	0.247**	0.244**	0.303**
Total productive maintenance	0.345**	0.243**	0.255**	0.335**
Autonomation	0.410**	0.300**	0.336**	0.355**
Value stream mapping	0.415**	0.301**	0.325**	0.360**
Continuous improvement	0.372**	0.324**	0.225**	0.342**

**Correlation is significant at 0.01 level (two-tailed)

(b)

	Unstandardised coefficients		**Standardised coefficients**	**t**	**Significance level**	**95% Confidence interval for B**	
	β	Std. error				Lower bound	Upper bound
Constant	5.888	0.403		14.617	**0.000**	5.095	6.680
Just-in-time	0.043	0.122	**0.023**	0.355	**0.723**	−0.196	0.283
Total productive maintenance	0.001	0.134	**0.000**	0.005	**0.996**	−0.262	0.264
Autonomation	0.527	0.121	**0.269**	4.356	**0.000**	0.289	0.765
Value stream mapping	0.379	0.123	**0.212**	3.080	**0.002**	0.137	0.621
Continuous improvement	0.218	0.144	**0.105**	1.515	**0.131**	−0.065	0.502

$R^2 = 0.258, F(5{,}334) = 23.255, p < 0.001$

(c)

	Radical Process Innovation	R&D investment	New technology investment	Radical process innovation
Technical Lean Practices	**0.470****	0.482**	0.316**	0.381**
Just-in-time	0.315**	0.344**	0.197**	0.253**
Total productive maintenance	0.356**	0.382**	0.221**	0.280**
Autonomation	0.405**	0.349**	0.317**	0.346**
Value stream mapping	0.441**	0.459**	0.309**	0.362**
Continuous improvement	0.398**	0.435**	0.252**	0.309**

**Correlation is significant at 0.01 level (two-tailed)

(d)

	Unstandardised coefficients		**Standardised coefficients**	**t**	**Significance level**	**95% Confidence interval for B**	
	β	Std. error				Lower bound	Upper bound
Constant	4.770	0.515		9.267	**0.000**	3.757	5.782
Just-in-time	−0.069	0.156	**−0.029**	−0.443	**0.658**	−0.375	0.237
Total productive maintenance	0.082	0.171	**0.033**	0.480	**0.632**	−0.254	0.418
Autonomation	0.580	0.155	**0.230**	3.757	**0.000**	0.277	0.884
Value stream mapping	0.593	0.157	**0.258**	3.771	**0.000**	0.284	0.902
Continuous improvement	0.335	0.184	**0.125**	1.820	**0.070**	-0.027	0.697

$R^2 = 0.270, F(5{,}334) = 24.717, p < 0.001$

4.2. Technical lean practices and process innovation (H1a & H1b)

Table 3(a) demonstrates Spearman correlations between the constructs and all respective items of TLPs and IPI, whereas Table 3(b) presents the respective multiple linear regression (MLR) model. Table 3(c) and (d) show the same results for TLPs and RPI.

The correlations and regressions regarding TLP are similar for both IPI and RPI (Table 3). Therefore, all technical lean tools are positively correlated with process innovation. However, the MLR analyses suggest different extents of these positive relationships. While JIT and Total Productive Maintenance (TPM) reveal the weakest effects, the correlation of continuous improvement (CI) with process innovation appears slightly stronger. Value stream mapping (VSM) and autonomation show the strongest and most significant relationships with IPI and RPI.

Although JIT has a central role in LM, the analyses indicate a weak impact on process innovation. JIT aims to reduce inventory levels and cycle time by streamlining production processes and entire supply chains (Chan, Yin, & Chan, 2010; Shah & Ward, 2003), which exposes problems in processes. Thus, to maintain constant production, disclosed problems must be solved in a short-term and resource-efficient way. This might provoke a hasty adoption of the first solution, increase pressure, and thereby hamper creativity and innovation performance (Chan et al., 2010). Furthermore, pull systems are by nature reactive (González-R, Framinan, & Pierreval, 2012) and thus they require less engagement and independent thinking from employees. Lastly, JIT is rather technically oriented, and entails streamlining and monotonous formalisations. These attributes are commonly claimed to limit independent thought and action, creativity, and innovative surroundings (Damanpour, 1991; Olivella et al., 2008; Weber, 2014). Potentially positive effects of JIT on process innovation are expected to be cancelled out by the mentioned negative impacts.

The same rationale applies to TPM. Its weak relationship with IPI and RPI may be attributed to its specific focus, especially that towards improving overall equipment effectiveness (OEE) and the exploitation of physical assets (Aminuddin, Garza-Reyes, Kumar, Antony, & Rocha-Lona, 2016). Exact time specifications like single minute exchange of die (SMED) or workers' increased responsibility for machine maintenance (autonomous maintenance) are expected to increase pressure and thereby limit room for creativity and innovation (Damanpour, 1991). Finally, TPM is implemented ineffectively in many cases (Belekoukias, Garza-Reyes, & Kumar, 2014), restricting and possibly even negating its impacts. Together, these negative effects most likely offset positive aspects of TPM, such as improvements in employees' autonomy and their workplace (Srinivasan, Ikuma, Shakouri, Nahmens, & Harvey, 2016).

The slightly stronger but still insignificant effects of CI are difficult to explain. According to Imai (1986), CI is the same construct as incremental innovation. Similarly, several authors characterise CI as a core lean value applicable to all other tools and techniques (Imai, 1986; Jasti & Kodali, 2015). Under close inspection, the CI variable generally shows higher values than other TLPs. This skewness distorts correlations, making eventually existing positive effects statistically undetectable. Another potential statistical error might arise from the low scale reliability of the process innovation dimensions, which only consist of 3 items. Nevertheless, especially problem identification techniques and tools supporting idea creation and teamwork (e.g. suggestion systems or brainstorming) (Liker & Meier, 2006; Rocha-Lona, Garza-Reyes, & Kumar, 2013) should be expected to enhance process innovation by fostering collaborative creativity.

The significant positive correlation between VSM and process innovation is most likely attributed to its strategical importance and comprehensive analytical nature regarding internal and external processes (Rother & Shook, 2003). VSM is partially perceived as a general and initial tool for lean implementation itself (Andreadis, Garza-Reyes, & Kumar, 2017; Belekoukias et al., 2014). Its potential to generate process innovations is shown in its ability to fundamentally redesign manufacturing systems based on holistic considerations of physical flow, information flow, and decision processes (Serrano, Ochoa, & De Castro, 2008).

The significant positive effect of autonomation might have several counterintuitive explanations. Everett and Sohal (1991) suggest that Andon systems increase workers' motivation and enhance mental processes that exist in play. Arguably, this increases innovative thinking. Furthermore, when mistakes are identified, the entire production line is stopped to ensure these do not reoccur (Liker & Meier, 2006). Although promoting short-term solutions, this raises awareness towards problems among all workers. Elevating problems and solving them in cross-hierarchical and team-based collaboration (Liker & Meier, 2006) generally enhances innovation (Friedrich & Ulber, 2017). Mistake-proofing, another aspect of autonomation, seems to make work processes monotonous and thereby hamper innovation at first glance. However, it might unleash unexpectedly positive effects: standardisation and simplification of work processes can make quality control unnecessary (Shingo, 1986), decrease pressure on employees, and thereby create the freedom necessary for innovative idea generation (Damanpour, 1991).

4.3. Human lean practices and process innovation (H2a & H2b)

Table 4(a) demonstrates Spearman correlations between the constructs and all respective items of HLPs and IPI, whereas Table 4(b) presents the respective MLR model. Table 4(c) and (d) show the same results for HLPs and RPI.

In general, the results of the analyses presented in Table 4 suggest a positive effect of HLPs on process innovation performance. Although the HLPs-related linear regressions appear to suffer from multicollinearity, all statistical assumptions for MLR are met (inter-item correlations < 0.8, tolerances < 1, variance inflation factor (VIF) < 5; Meuleman, Loosveldt, & Emonds, 2015; Hair, Black, Babin, & Anderson, 2014; Montgomery, Peck, & Vining, 2012; Grewal, Cote, & Baumgartner, 2004). The regression results provide insightful information regarding the tested hypotheses. Moreover, the relatively strong positive impact of structure and organisation is unexpected, and HLPs seem differently related with IPI than RPI.

Correlation effect size differences are small regarding H2a, and can therefore be neglected. This suggests that all HLPs have a positive influence on IPI. Most likely, this similarity and the insignificant regression parameters are caused by high inter-item correlations among HLP items. Interpreted from a practical perspective and underlined by the performed confirmatory factor analysis (CFA), these signs of multicollinearity indicate that most manufacturing organisations apply balanced approaches instead of focusing on specific HLPs in isolation. Perhaps, companies do this intentionally because they are aware of the importance of human practices for lean implementations and cultural changes (Sawhney & Chason, 2005). Another possible explanation is measurement distortions: the queried HLPs items are influenced by other improvement initiatives and general human resource (HR) practices (Shipton, Budhwar, Sparrow, & Brown, 2016). Lastly, the high inter-item correlations might arise from inherent interdependencies between the suggested HLPs, as implied by Shah and Ward (2003) to justify their bundled measurement. For instance, enhancing teamwork and collaboration can arguably simultaneously foster engagement and commitment.

Regarding H2b, similar sized correlations and signs of multicollinearity indicate that all HLPs have a balanced positive influence on RPI. However, the MLR model shows dominant influences of skill

Table 4
H2a: HLPs-IPI (a) Spearman correlations and (b) MLR model/H2b: HLPs-RPI (c) Spearman correlations and (d) MLR model.

(a)

	Incremental process innovation	Process adoption	Input material variation	Incremental process innovation
Human lean practices	**0.455****	0.337**	0.330**	0.427**
Skill development	0.382**	0.292**	0.273**	0.357**
Teamwork and collaboration	0.410**	0.289**	0.305**	0.385**
Engagement and commitment	0.411**	0.265**	0.295**	0.408**
Management and leadership	0.394**	0.275**	0.288**	0.387**
Structure and organisation	0.379**	0.333**	0.282**	0.326**

**Correlation is significant at 0.01 level (two-tailed)

(b)

	Unstandardised coefficients		Standardised coefficients	t	Significance level	95% Confidence interval for B	
	β	Std. Error				Lower bound	Upper bound
Constant	5.464	0.436		12.531	**0.000**	4.606	6.322
Skill development	0.151	0.163	**0.069**	0.923	**0.356**	−0.170	0.472
Teamwork and collaboration	0.355	0.188	**0.152**	1.883	**0.061**	−0.016	0.725
Engagement and commitment	0.274	0.165	**0.136**	1.666	**0.097**	−0.050	0.598
Management and leadership	0.158	0.183	**0.072**	0.866	**0.387**	−0.201	0.518
Structure and organisation	0.262	0.158	**0.124**	1.664	**0.097**	−0.048	0.572

$R^2 = 0.228, F(5,334) = 19.701, p < 0.001$

(c)

	Radical Process Innovation	R&D investment	New technology investment	Radical process innovation
Human lean practices	**0.515****	0.514**	0.362**	0.417**
Skill development	0.457**	0.471**	0.327**	0.353**
Teamwork and collaboration	0.443**	0.439**	0.327**	0.354**
Engagement and commitment	0.404**	0.409**	0.271**	0.342**
Management and leadership	0.445**	0.429**	0.307**	0.371**
Structure and organisation	0.475**	0.463**	0.341**	0.391**

**Correlation is significant at 0.01 level (two-tailed)

(d)

	Unstandardised coefficients		Standardised coefficients	t	Significance level	95% Confidence interval for B	
	β	Std. Error				Lower bound	Upper bound
Constant	3.798	0.539		7.040	**0.000**	2.737	4.859
Skill development	0.563	0.202	**0.199**	2.786	**0.006**	0.165	0.960
Teamwork and collaboration	0.334	0.233	**0.111**	1.434	**0.153**	−0.124	0.792
Engagement and commitment	0.055	0.204	**0.021**	0.272	**0.786**	−0.345	0.456
Management and leadership	0.127	0.226	**0.045**	0.561	**0.575**	−0.318	0.571
Structure and organisation	0.653	0.195	**0.240**	3.351	**0.001**	0.270	1.036

$R^2 = 0.288, F(5,334) = 12.973, p < 0.001$

development. Instead of merely focusing on technical skills, HLP-related skill development aims to create flexible, multi-functional, and cross-trained staff (Bhamu & Sangwan, 2014; Olivella et al., 2008). By stepping outside the boundaries of their usual work, employees can be expected to be more creative and radically innovative due to increased challenges and task complexity (Oldham & Cummings, 1996).

Counterintuitively, the MLR also suggests a relatively strong positive impact of structure and organisation on both IPI and RPI. A possible explanation for this unexpected observation might be that company-wide standardisation and structuration allows a quicker distribution of incremental and radical improvements. Also, lean standardisations might enable companies to adapt to change and innovations more flexibly (Berente & Lee, 2014), and especially contribute to creating an experiment-friendly environment instead of monotonous-discipline (Weber, 2014). Besides, standardised processes do not necessarily constrain creativity, but might be helpful for generating and successfully completing innovation projects. This is underlined by a multitude of innovation process models, such as idea development frameworks (Frishammar, Dahlskog, Krumlinde, & Yazgan, 2016) or Cooper's (2017) stage-gate concept. Lastly, the unexpected positive effect might also stem from product standardisations and dominant designs, which are found to enhance process innovation occurrence (Brem, Nylund, & Schuster, 2016).

In general, HLP-related correlations are weaker with IPI than with RPI. This might be due to different requirements of IPI and RPI. IPI build on existing processes (Kim et al., 2012), and therefore require technical knowledge. However, apart from hard skill development, HLPs predominately focus on rather general and soft aspects (e.g. teamwork, commitment, or leadership). These are mentioned in a wide range of literature related to the generation of creative and innovative environments (Shalley, Hitt, & Zhou, 2015). HLPs can therefore be expected to foster collaborative thinking outside of the box. In line with the results, this arguably rather enhances RPI.

Another observation is that regarding IPI, HLPs have stronger correlations with the actual occurrence than with process adoption or input material variation. This suggests a more direct influence of HLPs on IPI occurrence. In contrast, regarding RPI, HLPs are more strongly correlated with R&D investment than with actual RPI occurrence or new technology investment. Perhaps, the reason for this lies in companies' investment tendencies. HLPs and R&D are both intangible and long-term forms of investment, and both can be described as uncertain innovation inputs (Janger, Schubert, Andries, Rammer, & Hoskens, 2017). However, investments in new technologies are rather short-term, efficiency-focused, calculable, and partly even reversible (Chan et al., 2010). Hence, R&D and HR management might fall on a similar scale of willingness to invest, while distinct attributes determine intentions towards technology investments. Said uncertainty around converting innovation inputs to outputs (Duran, Kammerlander, Essen, & Zellweger, 2016) also explains the only moderate direct relationship between HLPs and actual RPI occurrence.

4.4. Process innovation and operational performance

Table 5(a) demonstrates Spearman correlations between the constructs and all respective items of IPI and OP, whereas Table 5(b) presents the respective MLR model. Table 5(c) and (d) show the same results for RPI and OP.

The correlation analyses presented in Table 5 suggest a moderate relationship of IPI and a strong relationship of RPI with OP. An explanation for this difference is offered by the nature of these two types of innovations. IPI generally improves existing processes (Kim et al., 2012), indicating that the potential extent of improvement through IPI is limited. This also explains the lower impact of IPI on flexibility, which is inherently bound to change. By its nature, RPI has larger and more holistic impacts on processes. Therefore, its stronger relationship with OP seems plausible.

Regarding both IPI and RPI, OP correlates strongest with the respective process innovation occurrence indicators instead of their input measures. This is consistent with common sense: not just efforts towards innovations but their actual occurrence determines their benefits. However, based on the nonetheless positive correlations, it can be assumed that efforts towards innovation (e.g. changing processes or making investments) are rewarded by more innovations and thus improve OP.

The MLR analysis indicates that all IPI items make significant contributions to improving OP. The fact that its actual occurrence has the highest impact on OP is in line with the arguments above. However, the results of the MLR model for RPI are unexpected. Compared with risky R&D expenditures, technology investment is rather transparent and calculable (Slack & Lewis, 2015). Hence, they should have a more direct and therefore stronger impact on OP. In contrast, new technology investment does not appear to influence OP significantly. Furthermore, actual RPI occurrence does not seem to impact OP more than R&D investment. Literature does not reveal potential explanations for these results.

4.5. Relating findings back to the research framework

Fig. 4 provides a visual overview of the Spearman correlation effect sizes and corresponding significance levels between the research framework's constructs.

Presumably, two main factors cause the rareness of strong interdependencies. First, the study included a diverse range of companies for an initial investigation. This broad coverage arguably increased data noise, manifesting itself in (1) a high dispersion and thus large residuals, and (2) levelled correlation and regression slopes (i.e. moderate effect sizes). Second, all MLR models suggest that additional unmeasured factors influence the dependent dimensions. This has a straightforward explanation: innovation capability is affected by many other initiatives, such as improvement programmes (Antony et al., 2016) or R&D collaboration and information systems (Trantopoulos et al., 2017; Un & Asakawa, 2015). Thus, besides acknowledging boundaries of statistical causality (Stuart, Ord, & Arnold, 2008), the characterised relationships should by no means be considered exclusive.

5. Concluding remarks, limitations, and future research

5.1. Theoretical implications

The results of this study indicate that all inter-dimensional correlations between the constructs are positive and moderate to strong, confirming all hypotheses, except for H1b. Thus, there remains little doubt that technical and HLPs improve incremental and RPI performance, in turn leading to measurable process innovation outputs in the form of improved OP. This supports the results of previous research, especially those from studies regarding the interdependency between lean and innovation (Antony et al., 2016; Arundel et al., 2007; Berente & Lee, 2014; Borrèl, 2013; Byrne et al., 2007; Chen & Taylor, 2009; Everett & Sohal, 1991; Johnstone et al., 2011; Jones & Linderman, 2014; Kim et al., 2012; Lewis, 2000; Lyons et al., 2013; Reinertsen & Schaeffer, 2005; Siemerink, 2014; Weber, 2014).

The results also corroborate inferences about positive effects of typical LM environments derived from general innovation management literature (Cooper, 1998; Damanpour, 1991; Dul & Ceylan, 2014; Fiates et al., 2010; Oldham & Cummings, 1996; Tomlinson & Fai, 2013). In

Table 5
H3a: IPI-OP (a) Spearman correlations and (b) MLR model/H3b: RPI-OP (c) Spearman correlations and (d) MLR model.

(a)

	Operational performance	Cost	Speed	Flexi-bility	Produc-tivity	Quality	Com-petitive-ness
Incremental process innovation	**0.460****	0.409**	0.420**	0.342**	0.375**	0.400**	0.411**
Process adoption	0.348**	0.292**	0.315**	0.270**	0.284**	0.308**	0.291**
Input material variation	0.327**	0.316**	0.281**	0.233**	0.278**	0.301**	0.309**
Incremental process innovation	0.428**	0.366**	0.403**	0.329**	0.347**	0.360**	0.377**

**Correlation is significant at 0.01 level (two-tailed)

(b)

	Unstandardised coefficients		**Standardised coefficients**	**t**	**Signifi-cance level**	**95% Confidence interval for B**	
	β	Std. error				Lower bound	Upper bound
Constant	8.710	1.087		8.012	**0.000**	6.572	10.849
Process adoption	0.948	0.300	**0.167**	3.155	**0.002**	0.357	1.538
Input material variation	0.782	0.284	**0.151**	2.751	**0.006**	0.223	1.341
Incremental process innovation	1.646	0.300	**0.305**	5.486	**0.000**	1.056	2.236

$R^2 = 0.244$, $F(3,336) = 36.149$, $p < 0.001$

(c)

	Operational performance	Cost	Speed	Flexi-bility	Produc-tivity	Quality	Com-petitive-ness
Radical process innovation	**0.531****	0.465**	0.429**	0.421**	0.432**	0.456**	0.474**
R&D investment	0.443**	0.413**	0.354**	0.340**	0.370**	0.361**	0.416**
New technology investment	0.390**	0.327**	0.310**	0.313**	0.312**	0.361**	0.358**
Radical process innovation	0.492**	0.422**	0.404**	0.386**	0.405**	0.430**	0.422**

**Correlation is significant at 0.01 level (two-tailed)

(d)

	Unstandardised coefficients		**Standardised coefficients**	**t**	**Signifi-cance level**	**95% Confidence interval for B**	
	β	Std. error				Lower bound	Upper bound
Constant	10.675	0.842		12.686	**0.000**	9.020	12.330
R&D investment	1.113	0.264	**0.249**	4.208	**0.000**	0.593	1.633
New technology investment	0.458	0.292	**0.096**	1.568	**0.118**	-0.116	1.032
Radical process innovation	1.291	0.283	**0.284**	4.560	**0.000**	0.734	1.848

$R^2 = 0.294$, $F(3,336) = 46.635$, $p < 0.001$

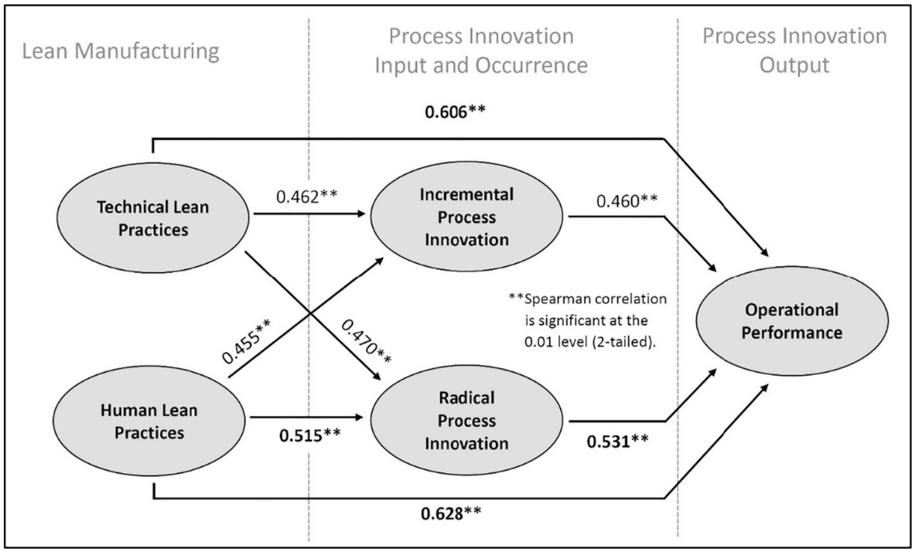

Fig. 4. Research results in relation to the research framework.

addition, the empirical evidence is aligned with all reviewed studies relating to process innovation input and occurrence with process innovation output in the form of OP (Ayhan et al., 2013; Gunday et al., 2011; Huergo & Jaumandreu, 2004; Kafetzopoulos et al., 2015; Lee et al., 2015; Schroeder et al., 1989; Trantopoulos et al., 2017).

As first of its kind, the present work contributes new and detailed insights into the nature of the investigated interdependencies. Holistic TLPs seem to have a greater potential to enhance process innovation than rather specific ones, whereas HLPs have close interrelations and thus influence process innovation more evenly. While lean practices appear to trigger the occurrence of IPI directly, their effect on RPI seems restricted by higher input-to-output uncertainty. Nevertheless, due to more holistic impacts when they occur, RPI appears to be a stronger mediator between LM and OP. These new observations complement studies investigating direct operational effects of LM. However, the data implies that there are more than the hypothesised impacts, and therefore suggests a more complex relationship between LM and OP than assumed by other studies.

Since H1b is rejected, the findings also challenge the suggestion that TLPs and RPI are negatively related. This stands in contrast to Arundel et al. (2007), Chen and Taylor (2009, 2012), and Chen et al. (2010). Perhaps, lean practices release otherwise wasted resources that can then be deployed to intangible, uncertain, and risky investments towards RPI (Borrèl, 2013; Lewis, 2000; Weber, 2014). Furthermore, contradicting Melnyk (2007), the differences between lean and innovation do not seem to hinder their integrated coexistence. A strategical negligence of innovation due to a too strong focus on efficiency in LM implementations seems, if existent at all, not to limit process innovation.

Similarly, the observations do not reflect negative impacts of LM on long-term flexibility and innovation (Lewis, 2000) as well as other drawbacks regarding novel and complex surroundings (Browning & Heath, 2009). This may be due to the comparably calculable nature of process innovation. Lastly, decentralisation does not seem to decrease companies' flexibility in adopting process innovations as hypothesised by Cooper (1998), possibly because standardisations can enhance their internal distribution.

In line with this argument, the results imply that indirect (i.e. TLPs) and direct (i.e. HLPs) lean standardisation practices enhance process innovation. This amalgamation of findings challenges several authors who indicate negative impacts of standardisation on innovation performance (Bouville & Alis, 2014; Chen & Taylor, 2009; Chen & Taylor, 2012; Damanpour, 1991; Olivella et al., 2008; Weber, 2014). In contrast, and aligned with the present findings, Weber (2014) mentions potential positive effects of standardisations in lean environments. Therefore, this work suggests that the impact of standardisations on innovation cannot be generalised, and it greatly depends on the purpose and especially the form in which they are implemented.

Lastly, the negative impacts of LM on employees' health and work environment (Bouville & Alis, 2014) due to deteriorating working conditions and increased stress levels (Mehri, 2006) do not hamper process innovation to the expected extent. Perhaps, western organisations have recognisably reduced these negative side-effects over the past years. Other suggested negative impacts on employees' commitment and freedom (Mehta & Shah, 2005; Parker, 2003) also seem non-significant. The same holds for general attributes of lean environments (e.g. uniformity, certainty, balance, or transparency), which some authors of the general innovation literature, e.g. Damanpour (1991), accuse of negatively influencing innovation performance.

As a main conclusion and partial answer to the further research requests of Berente and Lee (2014) and Weber (2014), the findings suggest that the multitude of LM attributes which positively influence process innovation performance outweigh potential and therefore nonetheless noteworthy negative characteristics. These results help to illuminate the lean manufacturing paradox between regulations and autonomy (Pakdil & Leonard, 2017), rigidity and flexibililty (Spear & Bowen, 1999), and efficiency and innovation (Jones & Linderman, 2014).

5.2. Practical implications

The results also yield several practical implications for manufacturing managers and their organisations. Most importantly, the findings advise to integrate efforts towards LM and process innovation. Since process innovation can be considered as an operational goal (Drohomeretski, Gouvea da Costa, Pinheiro de Lima, & Garbuio, 2014), its improvement should be made an expected outcome of LM implementations. More specifically, the findings suggest that lean practices must not be implemented with a mere focus on increasing employee efficiency to machine-like perfection, but should be treated as strategical guidelines or framework for optimisation and idea creation. For instance, to make use of their benefits while avoiding their negative effects, standardisations should not be implemented with a focus on monotonous formalisations and eliminating variability. Instead, it should be understood and employed as a method to quickly spread process innovations throughout organisations.

According to the results, lean tools seem to be applied in balance, meaning that organisations tend to cover a wide range of techniques even if individual tools are not thoroughly implemented. In addition, the analysis reveals that an ineffective implementation of some lean practices might hamper their positive effects. Based on these two findings, and the fact that all organisations face resource constraints, especially SMEs, decision makers are advised to thoroughly implement a manageable number of practices instead of superficially implementing a multitude of techniques. When reducing the number of implemented tools, the present results can help managers to prioritise practices according to their effect on process innovation. From that perspective, the tools and environments with significantly stronger relations to process innovation and OP should be implemented and fostered first.

Finally, managers can use the developed research framework and questionnaire for self-assessments of LM and innovation capability. This might help to identify the practices which require more thorough implementation to harvest benefits. Besides assessing individual locations and identifying room for improvement, companies can use the present work as a template to conduct internal benchmarking studies with key performance indicators (KPIs) between different sites, subsidiaries, or suppliers. Companies can track these KPIs longitudinally in purposely selected frequencies to monitor progress or identify trends.

5.3. Research limitations

Despite a multitude of precautions, the study is subjected to some noteworthy limitations. The reviewed literature was mainly related to the management of LM and innovation in industrial organisations. Other potentially interesting literature streams or disciplines were not reviewed extensively due to the work's focus and scope. Hence, caution is called for when generalising the findings to other fields of research. Moreover, the research framework was designed as formative construct, because a second order construct with reflective items and formative latent variables would have exceeded the scope of a self-administered online questionnaire. Formative constructs are less commonly applied, and besides some positive characteristics, entail several analytical disadvantages (Ford, 2017).

The applied research methodology entails three inherent but noteworthy limitations. First, the quantitative approach is limited in its depth of investigation, especially due to the coverage of all manufacturing sectors. Conclusions ignore the subjective nature and company-individual differences of LM implementations and their effects. Without time constraints, qualitative research such as recording participants' individual opinions, in-depth interviews, or case studies could have triangulated results. Second, the combination of global coverage, snowball-like sampling, and self-administered online questionnaires is especially prone to generate responses distorted by selection biases (e.g. non-random sampling) or participants' biases (e.g. overly optimistic assessments). Third, because time constraints did not allow longitudinal research, the cross-sectional design only portrays a snapshot picture of LM implementations. Therefore, presumably relevant time-related factors, such as delayed effects or organisations' development in OP, are neglected.

Further limitations arise from the samples' characteristics, where a greater sample size would provide more confidence for statistical analyses and their interpretation. Lastly, the study presents only a few of many factors influencing process innovation and OP. Overcoming these limitations is part of the future research agenda.

5.4. Future research

Although the present study offers first robust insights, it should be considered requiring more research. An initial approach could be developing more reliable and valid constructs, especially for the inherently multicollinear construct of HLP. Besides improving the research methodology, this would help practitioners prioritise HLP according to their positive impact.

On this basis, future studies could concentrate on certain company sizes, sectors, or regions and thereby create a greater understanding of the interdependency between LM and process innovation in specific cases or environments. Similarly, future investigations could cover LM and process innovation in industries with intangible products such as services.

To underpin the managerial and thus rather general findings of this work, researchers from other disciplines could contribute to the true understanding of underlying phenomena. Especially psychologists could shed light on employees' cognitive reactions to lean environments, and how exactly they affect innovation capability. Similarly, social scientists could study how cultural differences, which are conceptualised by a multitude of frameworks (e.g. Meyer, 2014), affect the interdependency between LM and process innovation. Finally, other influential factors could be characterised on process innovation and OP by applying the approach proven successful for this study. For instance, with a view to the future and as a next step of LM, researchers could investigate the technological and societal impact of industry 4.0 on organisations' process innovation performance.

Appendix A. Appendix A1

A confirmatory factor analysis (CFA) was conducted to (1) evaluate the reliability and validity of the research framework's dimensions and items, (2) gain additional justification for the comprising dimensions, and (3) investigate whether lean tools might have a reflective nature. Fig. A.1 shows the applied CFA model created using SPSS Amos and the maximum likelihood method (Brown, 2015). Considering the sample size ($N = 340$), the model revealed a good overall fit with the given data: (chi-square) $\chi^2 = 349.14$; (degrees of freedom) $df = 199$; $\chi^2/df = 1.754$, $p < 0.001$; (goodness-of-fit index) $GFI = 0.914$; (normed fit index) $NFI = 0.926$; (comparative fit index) $CFI = 0.966$; (root mean square error of approximation) $RMSEA = 0.047$ (Brown, 2015; Hair et al., 2014). All dimensions' items were significantly related at the 0.001 level. Since the CFA only served as an indication and was not critical for further analyses, potential model fit improvements (e.g. including error covariances) were not pursued. Table A.1 summarises all relevant measures regarding scale reliability and convergent and discriminant validity.

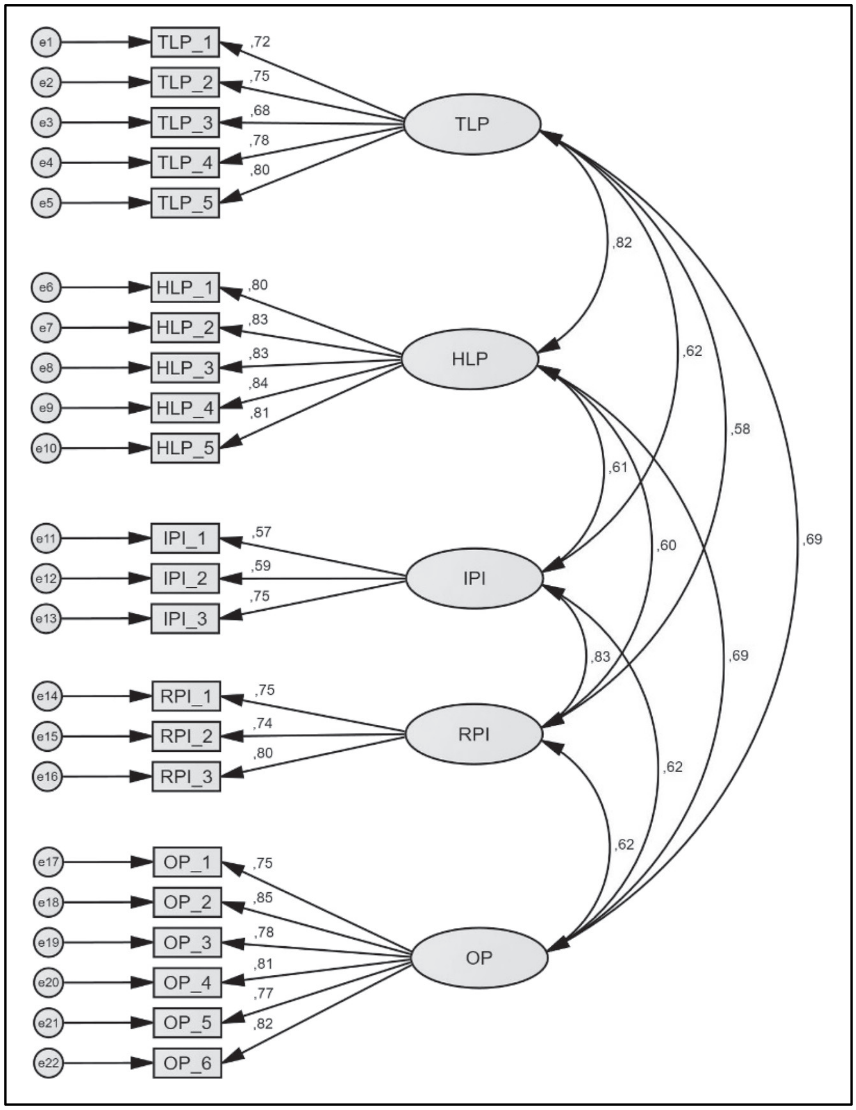

Fig. A.1. Structural equation model for the conducted CFA.

Table A.1
Reliability and convergent and discriminant validity of the research framework.

	Factor loading	Chron-bach's alpha	Composite reliability	Average variance extracted	TLPs	HLPs	IPI	RPI	OP
TLP	0.716	0.863	0.822	0.537	0.733				
	0.754								
	0.681								
	0.777								
	0.802								
HLP	0.801	0.912	0.913	0.677	0.821	0.823			
	0.829								
	0.835								
	0.842								
	0.807								
IPI	0.566	0.672	0.673	0.411	0.622	0.605	0.641		
	0.587								
	0.754								
RPI	0.750	0.807	0.808	0.584	0.582	0.601	0.828	0.764	
	0.744								
	0.797								
OP		0.913	0.913	0.638	0.689	0.691	0.616	0.618	0.799

(*continued on next page*)

Table A.1 (*continued*)

	Factor loading	Chron-bach's alpha	Composite reliability	Average variance extracted	TLPs	HLPs	IPI	RPI	OP
	0.755								
	0.852								
	0.780								
	0.814								
	0.766								
	0.821								

In general, the analyses demonstrated reliable scales with convergent and discriminant validity. Two exceptions were identified: (1) a low reflective reliability of the IPI dimension (evidenced by Chronbach's alpha and the composite reliability) and (2) a plausible limitation of discriminant validity between TLPs and HLPs as well as IPI and RPI (evidenced by the average variance extracted; Hair et al., 2014). However, this did not distort the statistical analyses conducted for the present study, since (1) formative items cannot be expected to correlate, and thus do not require reliability and convergent validity to be summarised (Ford, 2017), and (2) all hypotheses tests are evaluated on an individual basis.

The conclusions of finding the construct reliable and valid despite its formative tendency are twofold. First, it discovers that lean tools seem to be implemented jointly, and improvements in operational performance (OP) typically occur in a balanced combination. Second, this finding complements the theoretical justification of the dimensions and their cumulative variables (Hair et al., 2016; Hensley, 1999). Thus, it was considered reasonable to summarise the variables of each dimension into one Likert-like scaled construct.

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