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Operational practices for integrating lean and industry 4.0 – a dynamic capabilities perspective

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ABSTRACT
This article presents the findings of an exploratory survey conducted among 256 experts engaged in German manufacturing firms to explore practices related to integrating Lean with Industry 4.0. Using the Dynamic Capabilities framework as a theoretical lens, the study validates 43 practices organised into six dimensions: 'initiating', 'sensing', 'seizing', 'transforming', 'resources', and 'capabilities'. Theoretically, the research contributes by concretising the classical dimensions of Dynamic Capabilities and proposing the novel dimension of 'initiating', enhancing the theory's holism and applicability in the context of LM and I4.0 integrations. Managerially, the study provides a practical framework for self-assessment and strategic planning, emphasising the critical importance of early-stage practices related to 'change', 'resources', 'capabilities', and 'initiating'. These elements are crucial for triggering subsequent integration phases and ensuring successful execution. The framework addresses technology adoption, organisational culture, process optimisation, and workforce engagement, offering comprehensive guidance for integrating LM and I4.0. The contributions of this research hold value for the field of Operations Management as it provides empirical evidence on essential practices for effectively integrating Lean with Industry 4.0. Additionally, the study highlights the significance of Dynamic Capabilities as a means to comprehend and manage the complex interplay between these two approaches.

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SUSTAINABLE DEVELOPMENT GOALS
SDG 9: Industry, innovation and infrastructure

1. Introduction

Lean Management (LM) emerged as a worldwide business imperative focusing on waste reduction and continuous improvement (Womack *et al.*, 1990; Bhamu and Singh Sangwan, 2014). In contrast, Industry 4.0 (I4.0) holds great potential for transforming traditional operations through advanced technologies (Kagermann *et al.*, 2013). Since 2016, integrating both paradigms has attracted substantial attention in Operations Management (OM) (Bittencourt *et al.*, 2021). While both LM and I4.0 offer distinct advantages individually, nowadays, competitive advantages arise only when integrating both themes (Buer *et al.*, 2021). Furthermore, the rationale for integrating LM with I4.0 draws on increased operational performance, mutual synergies in the effectiveness of LM practices and I4.0 technologies, and potential increases in change capacities through a more holistic approach considering both people and technology (Bittencourt *et al.*, 2021; Tortorella *et al.*, 2021b). Consequently, integrating customer-centric LM practices with extended possibilities of technological advancements presents potential answers to even more challenging market requirements and individualisation trends (Cimino *et al.*, 2019; Ghobakhloo and Iranmanesh, 2021). Despite these proven rationales, the successful execution of integrations remains a challenge for many firms, necessitating exploratory research with a specific operational focus (Rossini *et al.*, 2022).

In contrast, prior research primarily focused on performance effects and derived which practices to be integrated with which technologies or superior implementation sequences (Komkowski *et al.*, 2022; Komkowski *et al.*, 2023b). Unfortunately, in contrast to 'why' and 'what', the level of 'how' firms may realise this is not yet part of a vital debate (Yilmaz *et al.*, 2022; Oliveira-Dias *et al.*, 2023). In the face of even higher failure rates for

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integrated approaches of LM and I4.0 transformations, research frequently calls for practical explorations and highlights the lack of action-oriented integration frameworks (Rossini *et al.*, 2022; Yilmaz *et al.*, 2022). This research gap can be placed at a more detailed level, and explorations should target contributions below the previous body of knowledge, also reflecting required resources and capabilities to enable action, which offers room for contributions with high value for firms seeking guidance on the operational aspects of integrating LM with I4.0 (Bokhorst *et al.*, 2022; Yilmaz *et al.*, 2022; Oliveira-Dias *et al.*, 2023).

Therefore, this paper aims to address this gap by empirically deriving a framework that informs the integration of LM with I4.0 on the 'how' level. Considering the introduced research gaps, the study draws upon the theory of Dynamic Capabilities (DC), which is well-suited for exploring how organisations execute such integrations and specifically emphasises the role of resources and capabilities (Walker *et al.*, 2015; Oliveira-Dias *et al.*, 2023). DC refer to an organisation's ability to sense, seize, and transform its resources and capabilities in response to changing environments and opportunities (Teece, 2018a).

This study aims to deepen the integration of two well-established research streams, LM and I4.0, by proposing an operational construct. As an exploratory survey, this article builds on the a previous qualitative research stage conducted by the team of authors (Komkowski *et al.*, 2023a). This preliminary study provided the input for the exploratory survey, which, as a sum, correspond to the norm of a sequential exploratory mixed-method research (MMR) and, through the use of advanced statistics, brings the qualitative findings to a more precise, valid, and reliable level (Edmondson and McManus, 2007; Creswell and Clark, 2017).

256 experts in LM and I4.0 who are engaged in German manufacturing firms are surveyed via a self-administered online survey. The answers were analysed following the procedure outlined by Flynn *et al.* (1994) for deriving operational frameworks and measurement constructs from exploratory surveys. Through this methodological approach, we address two research questions (RQ):

(1) How can firms execute an integration of LM with I4.0?; and,
(2) What resources, capabilities and processes are necessary to do so?

The findings present a framework that builds on the established dimensions of DC comprehended by an additional dimension to leverage the effectiveness. Furthermore, the model includes a set of required resources and capabilities that allow firms to integrate LM with I4.0 successfully.

This study contributes to both theory and practice. Hitt *et al.* (2016) found that DC are instrumental in understanding how firms overcome weaknesses and implement strategies. This understanding is evident in various contexts where the DC construct has been applied, leading to a more concrete grasp of the dimensions of sensing, seizing, and transforming (Leemann and Kanbach, 2022). However, it is interesting to note that, despite their pivotal role, the dimensions of resources and capabilities have not yet been fully concretised within this context especially concerning I4.0 (Kump *et al.*, 2018). Hence, our study contributes to theory by explicitly elucidating the complete set of DC dimensions. By doing so, we aim to advance the understanding of how firms practically apply the DC construct (Collis and Anand, 2021). From a practical standpoint, the findings offer concrete pathways for firms seeking to execute an integration of LM with I4.0. Previous research taught us about high failure rates even in singular integrations of LM or I4.0 (Pearce *et al.*, 2018; Correani *et al.*, 2020). Hence, the present challenge of integrating both themes includes even more risk of failure, which underpinnes the need for operational integration frameworks (Yilmaz *et al.*, 2022). Consequently, with its operational framework, this article presents a valuable contribution for firms seeking to execute the integration of LM and I4.0.

The rest of the paper is structured as follows. Section 2 provides a comprehensive overview of the theoretical background. Section 3 outlines the methodology employed in this study. Subsequently, Section 4 summarises the survey results. In Section 5, the findings are thoroughly discussed, with a focus on their implications for both theory and practice. Section 6 concludes the paper by summarising the key findings, emphasising their managerial implications, and discussing their broader significance in OM.

2. Theoretical Background

2.1. Integration of Lean Management with Industry 4.0

Previous research explored the integration of LM with I4.0 on different levels, namely: Why (target dimensions, outcomes, and effects), what (practices and principles), and how (pathways and levers) (Komkowski *et al.*, 2022; Komkowski *et al.*, 2023b). The core aspects of each level will be aggregated within this sub-section.

On the highest level, the authors explored the effects of integrating LM with I4.0. Several authors derived that LM and I4.0 hold the power to improve operational performance individually but contribute more than their individual effects in the case of integrated approaches (Buer *et al.*, 2021; Rossini *et al.*, 2022). In contrast, Bokhorst *et al.* (2022) found that firms who focus on LM achieve comparable levels of operational performance to firms integrating LM with I4.0 concerning quality, delivery, flexibility, and cost. In more detail, the superiority of integrated approaches was confirmed for the cost dimension only (Bokhorst *et al.*, 2022). Furthermore, Tortorella *et al.* (2021b) derived that performance effects are valid on workplace and value stream levels but not on extended value streams. These findings indicate that presently firms need to adapt their approaches to integrating LM with I4.0 according to the intended achievements of operational performance, including contingencies.

Research concerning the mid-level of integrated practices and principles intends to explore which LM elements are integrated with single technologies. Initial contributions addressed principles, while more recent publications evaluate the interrelations on the level of single practices (Ciano *et al.*, 2021; Shahin *et al.*, 2023). Furthermore, research elaborated on the specific relevance of LM or I4.0 elements, superior combinations, and potential pathways for executing integrations (Cifone *et al.*, 2021; Santos *et al.*, 2021; Tortorella *et al.*, 2021a).

Third, previous research revealed concrete modes of action regarding how firms may execute or realise the integration of LM with I4.0. Fundamentally, three integration directions can be distinguished: LM as the dominant theme, a balanced consideration of both themes and I4.0 as the dominant theme (Komkowski *et al.*, 2022). If LM represents the dominant theme, authors consider LM a prerequisite and suppose to develop an appropriate maturity before integrating I4.0. Generic success factors are created via LM and are auxiliary forces in I4.0 integrations. These act as the DC for an expedited integration of I4.0 and include a learning culture, top-level leadership, forming cross-functional teams, frameworks for change governance, and training programmes (Buer *et al.*, 2021; Pozzi *et al.*, 2021). In the case of a balanced consideration, the authors confirm the role of LM as a mediator for I4.0. However, the leveraging impact of I4.0 is also highlighted, and businesses are recommended to combine both ideas to become smart and lean (Kamble *et al.*, 2020). The third research stream considers I4.0 dominant due to its ability to overcome LM constraints (Sanders *et al.*, 2016; Rosin *et al.*, 2020). There is widespread agreement regarding the transformative power of data and the speed of information, and specific use cases demonstrated I4.0 employing LM techniques (Davies *et al.*, 2017; D'Orazio *et al.*, 2020; Pagliosa *et al.*, 2021).

2.2. Dynamic Capabilities

OM was regularly criticised for lacking theoretical advancements in light of its practical research focus, preferably drawing theories from other disciplines. In the range of applied theories, DC represent the most frequently adopted theory in OM originating from strategic management (Teece *et al.*, 1997; Walker *et al.*, 2015). We decided to rely on DC based on its exploratory power when researching organisational development, e.g. integrating LM with I4.0 (Anand *et al.*, 2009; Secchi and Camuffo, 2016; Kurtmollaiev, 2020).

The theory of DC intends to inform firms on how to respond to changes in the external environment by adapting, integrating, and reconfiguring its resources targeting to develop or sustain competitive advantages (Teece, 2018a). The modes of action and feasibility of developing DC, as well as their presence in general, remain part of an everlasting debate, and we rely on the most widely agreed core elements of the framework if related to innovation and resource-value creation (Katkalo *et al.*, 2010; Peteraf *et al.*, 2013; Teece, 2014; Kump *et al.*, 2018). These elements are illustrated in Figure 1.

The focus of this research is to derive a model for executing the integration of LM with I4.0. Hence, of the DC framework relevant are 'sensing', 'seizing', 'transforming', 'dynamic and ordinary capabilities', 'valuable, rare, inimitable, and nonsubstitutable (VRIN) and non VRIN resources', and 'strategy'. Following Teece (2018b), 'sensing' refers to an organisation's ability to identify changes and opportunities in its external environment. 'Seizing' involves the organisation's capacity to act upon the previously sensed opportunities. 'Transforming' is the capability to adapt and reconfigure an organisation's internal resources and processes. 'Dynamic capabilities' are the distinctive, flexible, and adaptive competencies that enable an organisation to respond effectively to changing environments. 'Ordinary capabilities', on the other hand, represent an organisation's basic operational competencies necessary for day-to-day functioning. 'Non VRIN resources' are the basic inputs and assets that most firms possess, while through their nature, VRIN resources are those that allow a competitive advantage. 'Strategy' refers to the organisation's plan or approach to achieve its long-term goals and objectives, which in the present research includes integrating LM with I4.0. The construct's remaining elements can be considered lagging and not informing how to integrate LM with I4.0.

Previous research successfully employed DC in exploratory studies concerning LM or I4.0 integrations (Garbellano and Da Veiga, 2019; Felsberger *et al.*, 2020; Ghobakhloo and Fathi, 2020). Contributions concern the

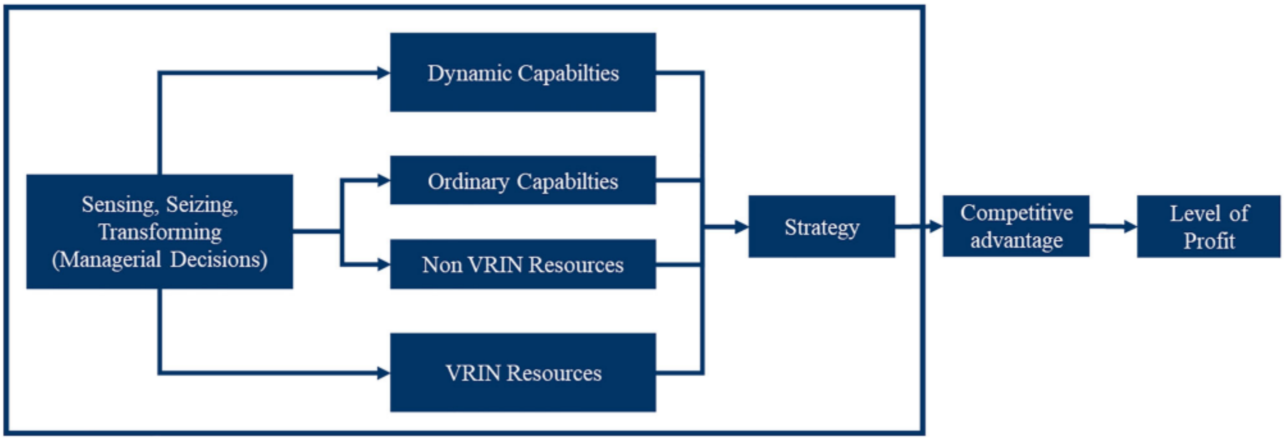

Figure 1. Dynamic Capabilities framework (Teece, 2014). The dynamic capabilities framework, along with its components of initiating, sensing, seizing, resources, capabilities, strategy, is emphasised using a visual representation in the form of a box.

role of learning, pathways of adapting capabilities, deriving specific resources and capabilities, and infrastructural ambidexterity (Demeter *et al.*, 2021; Mohaghegh *et al.*, 2021; Dixit *et al.*, 2022; Saabye *et al.*, 2022; Csiki *et al.*, 2023). Hence, DC represent a promising vehicle for deriving insightful contributions within the research focus.

3. Methodology

This study aims to derive an operational framework for integrating LM with I4.0 that can support firms in integrating LM with I4.0. Therefore, this quantitative study benefits from two previous exploratory research stages (Edmondson and McManus, 2007). In total, the individual research stages follow the norm of sequential exploratory MMR, with each stage informing the subsequent stage, which was chosen based on the current low level of executable knowledge (Edmondson and McManus, 2007; Buer *et al.*, 2021; Collis and Anand, 2021).

Fundamentally, a systematic literature review strictly following the procedure as outlined by Tranfield *et al.* (2003) and adjusted to OM by Thomé *et al.* (2016) aggregated the knowledge base of LM and I4.0 integrations with a sample of 111 articles published in high-ranking and practitioner journals and informed the following qualitative research stage (Komkowski *et al.*, 2022; Komkowski *et al.*, 2023b).

Subsequently, a qualitative stage conducted an inductive Thematic Analysis (TA) of 16 semi-structured interviews with experts in LM and I4.0 engaged in large German manufacturing firms (Komkowski *et al.*, 2023a). The TA strictly followed the principles outlined by Braun and Clarke (2006). The German research focus was chosen due to the solid LM tradition and a technologically characterised industrial landscape (Bloom *et al.*, 2014; Fukuda, 2020). This research stage contributed seven potential phases and 200 items for executing the integration of LM with I4.0. These phases not only consider all dimensions of the DC theory, but propose additional entities potentially allowing an extension of the theory, namely 'initiating' and 'sustaining'.

Finally, in the present article, the results from the previous research stages were quantitatively evaluated following the principles of explorative surveys to derive operational frameworks in the field of OM (Flynn *et al.*, 1994; Forza, 2002; Boateng *et al.*, 2018). The methodological approach of this final stage is summarised in Figure 2.

First, we derived survey items and developed our measurement scale. This included a content validity assessment to identify the most relevant items from the previous research stages, followed by a pilot survey for refinement. Second, we selected a suitable sample and collected data by administering the survey to experts in German manufacturing firms, totaling 205 valid responses. Third, maintaining research integrity, the third step involved assessing potential biases that might have affected our data, to ensure the unbiased derivation of our framework. The final step includes rigorous statistical analysis to derive insights, alongside reliability and validity assessments to ensure the robustness and accuracy of our findings. The following subsections provide a more detailed explanation of each step.

3.1. *Item generation and scale development*

Due to the exploratory research status, we combined a deductive and inductive approach for the exploratory framework development and item generation (Hinkin, 1995). Through 16 semi-structured expert interviews, we gathered valuable insights and data. The experts were purposively sampled, each with at least five years of

Figure 2. Methodology (based on Flynn *et al.*, 1994; Forza, 2002; Boateng *et al.*, 2018). The methodological approach involves generating items and developing scales, gathering samples and data, assessing bias, and refining the framework through evaluation.

experience in actual integrations of LM with I4.0 within German manufacturing firms (Kumar *et al.*, 1993; Tortorella *et al.*, 2021a; Kayikci *et al.*, 2022). The interviews yielded 200 potential items, categorised into seven distinct phases related to the integration of LM with I4.0. The interview process was guided by a carefully designed interview guide, informed by the findings from a previous SLR conducted for this study. The complete interview guide can be found in Appendix 1 for a more detailed reference. After conducting the TA, the content validity of the items was assessed based on a 3-point Likert scale evaluation of 12 academic and industrial experts, leading to a reduced number of 99 items being considered 'essential' at the cut-off value for the content validity ratio of .56 (Lawshe, 1975; Forza, 2002; Wilson *et al.*, 2012). Consequently, these items remained in the instrument.

Subsequently, the remaining items were pre-tested with 18 academic and industrial experts not considered in the content validity assessment. This led to 91 refined and validated survey items (Boateng *et al.*, 2018). A 5-point Likert scale ranging from strongly disagree to agree strongly was chosen based on experiences from previous research and to prevent fatigue introduced by more differentiating rating scales as a response to the high number of items (Shah and Ward, 2007; Jebb *et al.*, 2021; Oliveira-Dias *et al.*, 2023). The final set of survey items is enclosed in Appendix 2. Finally, a pilot study was administered using Qualtrics with a sample size of 30 participants (Johanson and Brooks, 2010). Answers from this preliminary stage were not considered in the final analysis. Learnings from this stage lead to minor modifications primarily targeting improved understandability of items.

3.2. *Sampling and data gathering*

The sample of this study consists of experts engaged in LM and I4.0 in German manufacturing firms (Forza, 2002). At the time of the survey, LinkedIn offered access to 4.100 experts holding expertise in LM and I4.0 and being engaged in German firms. LinkedIn was validated as a reasonable platform for participant recruitment in previous research (Stokes *et al.*, 2019). From this population, a randomly selected sample of 2.500 experts was drawn to reduce potential biases (Baltar and Brunet, 2012). Based on estimated completion rates of approximately 10%, 250 participants were targeted, slightly above the median in management-related research (Scandura and Williams, 2000).

Following Forza (2002), participants were first contacted and second invited to participate voluntarily and anonymously. With invitations through LinkedIn, participants were provided comprehensive information regarding the study's motivation, anticipated duration, and privacy details. A direct link to the survey was included, enabling easy access for those interested in participating. No reminders were sent as non-respondents could not be identified due to anonymity reasons (Shah and Ward, 2007; Christensen *et al.*, 2015). Table 1 outlines the sample profile.

The main study was administered following the pilot study and revealed 256 responses based on the sample of 2.500 invited subject matter experts engaged in German manufacturing firms within two months (Keramida *et al.*, 2022). Of these 256 responses, 205 complete answers were considered for analysis. As participants were sampled randomly based on their profile fulfilling the recruitment characteristics, the sampling shares both a purposive and a random element (Forza, 2002). Anyhow, in this exploratory stage and due to the specific research focus, experts are the only way forward to derive reasonable insights (Shah and Ward, 2007). Consequently, bias is analysed in the following subsection.

3.3. *Bias evaluation*

As with every research method, surveys are prone to potential biases. Concerning coverage bias, an evaluation

Table 1. Sample profile

Variables (n = 205)		
Origin	Frequency	Percentage
Germany	205	100%
Industry		
Services*	41	20.00%
Manufacturing	147	71.71%
Other	17	8.29%
* PRIMARILY CONSULTING		
Job function		
Lower Mangement	23	11.22%
Higher Management	30	14.63%
Employee	36	17.56%
Middle Management	50	24.39%
Operational Excellence Manager	42	20.49%
Other	24	11.71%
Employees		
< 10	19	9.27%
11 - 50	15	7.32%
51 - 250	13	6.34%
250 - 500	13	6.34%
> 500	145	70.73%
Revenues		
No answer	29	14.15%
< 2 Mio. €	19	9.27%
10 - 50 Mio. €	16	7.80%
2 - 10 Mio. €	11	5.37%
> 50 Mio. €	130	63.41%
Experience Lean		
No answer	9	4%
1 - 3 years	63	31%
3 - 5 years	32	16%
5 - 8 years	28	14%
> 8 years	73	36%
Experience Industry 4.0		
No answer	10	5%
1 - 3 years	56	27%
3 - 5 years	44	21%
5 - 8 years	44	21%
> 8 years	51	25%

comparing the shares for each company size of the respondents to the population of German firms by computing x2-test statistics (Destatis, 2020). Results indicate that the sample is biased towards large firms (x2 = 273,512, df = 2, $p < 0{,}001$). In this case, large firms tend to offer more insightful results, as demonstrated in previous research, and participants were intentionally recruited from large firms (Shah and Ward, 2007).

Second, due to anonymity, nonresponse biases cannot be assessed directly. Instead, differences between early and late respondents were analysed. Late respondents were defined as the last third of participants (Gruber *et al.*, 2010). An independent samples t-test confirmed no significant differences (lowest p-value > 0,9) in means of respondents' characteristics of experience, company size, and revenues between early and late respondents (Armstrong and Overton, 1977; Datta *et al.*, 2005).

Third, common method bias was evaluated using Harman's one-factor test (Podsakoff *et al.*, 2003). Common method bias requires further attention if factors analysis across all measurement items results in one factor (Shah and Ward, 2007). Exploratory factor analysis (EFA) revealed 16 factors with Eigen values greater than one confirming that common method bias is unlikely to be problematic (Fuller *et al.*, 2016).

Finally, assumptions of multivariate analysis require evaluation. Both Kolmogorov-Smirnov and Shapiro-Wilk tests present p values below .001. Hence, non-normality assumptions are violated, which requires a more detailed analysis. Therefore each item's skewness and kurtosis were evaluated with thresholds of ≥ 2.0 and ≥ 7.0 (Curran *et al.*, 1996; Kamble *et al.*, 2020). Three items were excluded, exceeding these limits. Furthermore, responses were only considered if missing data accounts for less than 10%, with mean imputation for missing data. The absence of outliers was confirmed using box plots (Eekhout *et al.*, 2014; Watkins, 2018). Finally, item 15_1 had to be excluded from the analysis based on SPSS anomaly detection. Additionally, the appropriateness of the data was evaluated by confirming a sizable number of correlations exceeding +0.30, Kaiser-Meyer-Olkin (KMO) value with .834 exceeding the threshold of 0.70, as well as Bartlett's test of sphericity (BTS) with chi-square 3963.47 and $p = < 0.001$ (Hair *et al.*, 2010; Hoelzle and Meyer, 2013; Lloret *et al.*, 2017). Although skewness and kurtosis fulfil the basic assumptions of multivariate analysis, we decided to employ unweighted least squares extraction and oblique rotation as a robust selection for factor analysis of non-normal and ordinal data (Mooijaart, 1985; Curran *et al.*, 1996; Costello and Osborne, 2005).

3.4. Scale evaluation

Drawing upon relevant examples from previous research, we employed a three-step approach to evaluate the reliability and validity of our measurement instrument, with an additional concluding mean ranking of items in the context of exploratory surveys (Flynn *et al.*, 1994; Forza, 2002; Leoni *et al.*, 2022). Figure 3 outlines the applied procedures.

In our study, we employed a robust set of scale evaluation techniques to ensure the reliability, validity, and ranking of the measures used. First, for assessing reliability, we employed the internal consistency method, which involved calculating Cronbach's alpha values and inter-item correlations (CITC) for each scale (Nunnally, 1978; Hensley, 1999; Shah and Ward, 2007). These analyses helped establish the internal consistency and coherence of the scale items by applying the thresholds of exploratory research of $\alpha \geq 0.6$ and $\rho \geq 0.3$ and iterative refinement of scales (Nunnally, 1978; Forza, 2002; Shah and Ward, 2007).

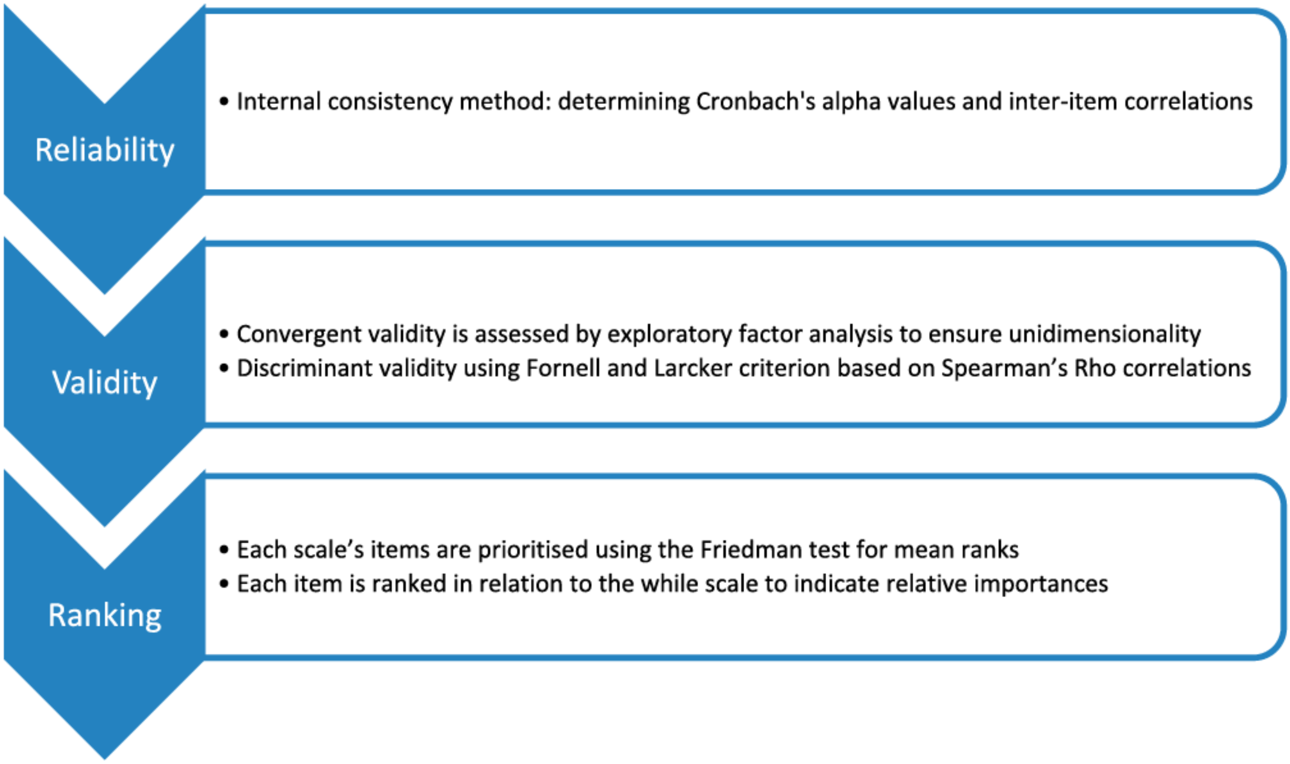

Figure 3. Scale evaluation (based on Flynn *et al.*, 1994; Forza, 2002; Leoni *et al.*, 2022). The evaluation of the scales involves the examination of reliability, validity, and item ranking.

Secondly, we examined the validity of our scales. To verify convergent validity, we performed EFA to ensure unidimensionality of the constructs (Spector, 1992; Flynn *et al.*, 1994; Hensley, 1999; Conway and Huffcutt, 2003). Items with factor loadings below 0.4 were removed based on the significance of the sample size (Hair *et al.*, 2010). KMO values and BTS were evaluated for each subscale (Hair *et al.*, 2010; Hoelzle and Meyer, 2013; Lloret *et al.*, 2017).

Third, we assessed discriminant validity using heterotrait-monotrait (HTMT) ratios and the Fornell and Larcker criterion based on Spearman's Rho correlations to confirm that the constructs were distinct from one another (Fornell and Larcker, 1981; Åhlström and Westbrook, 1999; Leoni *et al.*, 2022). The convergent validity was evaluated for all scales in their final composition by comparing the square root of average variance extracted (AVE) for a scale with the correlation to the other scales of a construct (Fornell and Larcker, 1981; Leoni *et al.*, 2022).

Finally, we employed ranking techniques to determine the relative importance of each item within the scales. This was accomplished by utilising the Friedman test for mean ranks, allowing us to prioritise each item in relation to the entire scale, offering valuable insights into their relative significance.

Concerning reliability, six out of seven scales fulfil the defined thresholds of internal consistency and remain in the framework for further evaluation. Based on Cronbach's alpha values, we revealed that four derived scales exceed alpha values of .700, representing good reliability even for mature scales, while one scale had to be dropped, not fulfilling the threshold for new scales (Nunnally, 1978).

Concerning validity, content validity was established throughout the rigour of the previously outlined research steps. Hence, we evaluated convergent and discriminant validity (Flynn *et al.*, 1994). The evaluation of convergent validity concerns the degree of similarity among items assessing the same construct. In contrast, discriminant validity reflects the degree of distinction between items of different constructs (Forza, 2002). In conclusion, convergent validity was confirmed promptly for four of six subscales'. In comparison, the assessment of 'seizing' and 'transforming' revealed two underlying factors leading to the formation of two additional subscales each (Flynn *et al.*, 1994). Table 2 presents the outcome of the reliability and convergent validity assessment.

Concerning discriminant validity, Table 3 demonstrated all square roots of AVE exceeding the correlation to other scales, which confirms discriminant validity.

Finally, each scale's items are prioritised using the Friedman test for mean ranks to evaluate their relative importance (Kuula *et al.*, 2012; Godinho Filho *et al.*, 2017). The results of these calculations are presented

Table 2. Reliability and convergent validity of scales

Scale	Cronbach's alpha	# of items in final scale	# of items deleted (CITC)	# of items deleted (loading)
Initiating	.683	5	1	1
Sensing	.660	6	4	2
Seizing				
(1) Transparency	.708	3	/	0
(2) Governance	.678	5	/	2
Transforming:				
(1) Culture & Change	.717	7	0	0
(2) Execution	.718	6	2	15
Resources	.647	6	6	3
Capabilities	.737	5	1	1

Table 3. Discriminant validity of scales

				Seizing				Transforming	
		Initiating	Sensing	Transparency (Seizing 1)	Governance (Seizing 2)	Resources	Capabilities	Culture & Change (Transforming 1)	Execution (Transforming 2)
	Initiating	.551							
	Sensing	.399**	.506						
Seizing	Transparency (Seizing 1)	.255**	.115	.630					
	Governance (Seizing 2)	.412**	.406**	.247**	0,659				
	Resources	.370**	.339**	.288**	.460**	.500			
	Capabilities	.536**	.453**	.287**	.490**	.490**	.610		
Transforming	Culture & Change (Transforming 1)	.351**	.419**	.302**	.415**	.442**	.501**	.530	
	Execution (Transforming 2)	.395**	.413**	.418**	.459**	.425**	.454**	.486**	.550

** significant at $p < .001$

within the following subsection and each subscale's presentation.

4. Results

Based on the reliability and validity assessments, this subsection presents the results outlining each scale, including its final composition and descriptive statistics aligned with the principles of exploratory surveys (Forza, 2002).

4.1. *Initiating*

The DC framework classically starts with 'sensing', which informs and triggers the subsequent stages, e.g. seizing or transforming. While 'sensing' intends to explain how firms may identify opportunities, our survey participants raised the point that firms potentially benefit from developing a previous capability that streamlines and triggers 'sensing' practices. We labelled this capability as 'initiating'. Table 4 presents the final items representing and characterising the 'initiating' scale. The items are sorted according to their mean ranks to indicate their relative relevance (Godinho Filho *et al.*, 2017).

'Initiating' practices intend to trigger the subsequent elements of the DC construct. From the validated set of items, three items reflect practices concerning target states, namely: visualising target states, e.g. pictures of a pilot area (1_7), developing long-term guiding principles as guidelines (1_6), and establishing internal benchmarks for specific LM and I4.0 practices (1_5). Besides these items, leadership plays a key role, e.g. in developing a convincing change strategy (1_2) or training managers to identify waste/improvement potentials (1_3). Typically, target state developments play a pivotal role in senior and middle management, emphasising leadership's important role in forming the capability of 'initiating' (Rotemberg and Saloner, 2000). Concerning relative relevances, one item falls into the first quartile, two fall into the second quartile, and the remaining two fall into the third and fourth quartiles. Based on these rankings, the general relevance of this subscale can be assumed to be higher than average.

Table 4. Validated items of Initiating

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Loading	CITC	Alpha
1_7	4.45	5	0.78	1	3.32	Q1	.508	.427	.683
1_3	4.40	5	0.83	1	3.25	Q2	.498	.441	
1_2	4.38	5	0.77	1	3.20	Q2	.526	.449	
1_6	4.15	4	0.94	1	2.78	Q3	.623	.435	
1_5	3.98	4	0.94	1.5	2.45	Q4	.591	.456	

4.2. Sensing

Sensing capabilities refer to firms identifying opportunities from their environment (Teece, 2018b). In the original definition, the field of 'sensing' is rather broad and concerns technological developments, customer needs or market mechanisms, but mainly from an external perspective of an organisation (Teece, 2014). Other authors also include internal perspectives, but contributions tend to rely on the original external focus (Kump *et al.*, 2018). Six items characterise the scale in the context of LM and I4.0 integrations, presented in Table 5.

Interestingly, besides confirming classical levers of regular external stimulus (2_7), our results highlight the importance of internal levers of regular reflection of own approaches (2_10), focus on high motivation for change among involved employees (2_4), focus on the vision/target state of a company (2_1), defining, communicating and breaking down a vision (2_2), and conducting interviews with staff (2_3) as most relevant items for 'sensing' capabilities. The composition of the scale is derived based on the focus on LM and I4.0 integrations and somehow deviates from the original external focus highlighting and valuing internal practices, with item 2_10 being part of the first quartile of rankings across the items of the proposed framework.

4.3. Seizing

Seizing can be translated into how firms decide upon their sensed opportunities (Teece, 2018b). We searched for specific practices to inform how firms may concretise and develop this capability to specify 'seizing', which lays in between and connects 'sensing' and 'transforming' within LM and I4.0 integrations.

The reliability of the initial scale led to the elimination of a reasonable number of items. Hence, EFA was employed and revealed two underlying factors, which will be presented separately within this subsection. The first subscale is presented in Table 6.

This subscale's items concern transparency aspects, namely 'facilitate transparency on status and progress through reporting apps' (3_8), 'each project should be guided by an easily measurable goal' (3_7), and 'developing a key performance indicator system that enables derivation and monitoring of projects' (3_6). Additionally, Table 7 presents the second subscale.

The second subscale concerns aspects related to governance, namely 'initiating a broad communication of progress' (3_5), 'inclusion of management for solving hurdles' (3_3), 'focus reporting on demonstrating results on the shopfloor' (3_2), 'involving one level of hierarchy higher than affected areas' (3_4), and 'seizing LM practices primarily in a coaching-based approach (3_10).

4.4. Transforming

Firms can realise what was previously sensed and seized through 'transforming' capabilities (Teece, 2018b). In the present study, most of the items were derived concerning this DC dimension. While the reliability assessment confirmed the whole scale except for two items, EFA revealed two underlying factors forming two separate subscales and fulfilling the defined thresholds.

The final items of the first subscale are: general aspects of good change management remain relevant (4_1), opening feedback channels to promote continuous development (4_2), using digitalisation-based transparency to communicate successes (4_4), specifically developing required attitudes for digitalisation (4_6), actively using managers' role model function (e.g. use of digital practices) (4_9), focusing workshop formats that involve all people required to evaluate and change a process (4_20), and allowing operational staff to review new practices at regular intervals (4_24). Based on the close relationship to cultural and change management practices, we labelled this subscale 'culture and change'. Subscale 1 is presented in Table 8.

Table 5. Validated items of Sensing

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Loading	CITC	Cronbach's Alpha
2_10	4.50	5	0.72	1	4.34	Q1	.441	.354	.660
2_4	4.14	4	0.94	1	3.57	Q3	.590	.461	
2_1	4.11	4	0.88	1	3.51	Q3	.441	.342	
2_2	4.07	4	0.92	1	3.45	Q3	.617	.476	
2_3	3.83	4	1.14	2	3.10	Q4	.493	.386	
2_7	3.81	4	1.04	2	3.02	Q4	.417	.342	

Table 6. Validated items of Seizing 1: Transparency

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
3_7	4.46	5	0.74	1	2.27	Q1	.769	.539	.708
3_6	4.13	4	0.99	1	1.95	Q3	.725	.539	
3_8	3.94	4	0.99	2	1.78	Q4	.558	.472	

Table 7. Validated items of Seizing 2: Governance

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
3_5	4.42	5	0.80	1	4.12	Q2	.689	.445	.678
3_3	4.27	4	0.87	1	3.93	Q2	.733	.542	
3_2	3.98	4	1.05	2	3.35	Q4	.627	.412	
3_4	3.95	4	0.95	2	3.30	Q4	.674	.436	
3_10	3.66	4	1.12	1	2.87	Q4	.560	.351	

Table 8. Validated items of Transforming 1: Culture and change

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
4_9	4.60	5	0.68	1	4.35	Q1	.521	.410	.717
4_2	4.54	5	0.72	1	4.26	Q1	.689	.561	
4_1	4.49	5	0.80	1	4.20	Q1	.493	.392	
4_4	4.52	5	0.72	1	4.13	Q1	.424	.383	
4_20	4.38	5	0.73	1	3.81	Q2	.497	.417	
4_6	4.36	5	0.82	1	3.79	Q2	.498	.500	
4_24	4.24	4	0.80	1	3.45	Q2	.523	.418	

Concerning the ranks of this subscale's items evaluated across the whole scale, all items are part of the first or second quartile indicating a high relevance of this subscale for the overall framework. While participants confirmed the overall relevance of previously established change management practices (4_1), the findings outline several practices holding a high relevance specifically for integrating LM with I4.0.

Additionally, the final items of the second subscale are: Nudging digital solutions in improve phases of DMAIC/PDCA (4_17), developing a responsibility-oriented decision-making and accountability system (4_18), developing a KPI set concerning relevant variables of the entire value stream (4_19), employing a coaching-based implementation approach (4_26), using alternating implementation steps between LM and IT (4_27), training a broad mass in the use of LM and I4.0 change blueprints (4_29). Based on the close relationship to executing levers, we labelled this subscale 'execution'. Subscale 2 is presented in Table 9.

Two items of this subscale rank in the third quartile and the remaining four items rank in fourth quartile. Based on the items' ranking, a lower relevance can be assumed relating to the other items of the framework.

4.5. Resources

The DC framework encompasses tangible and intangible assets as resources organisations employ to facilitate adaptation and responsiveness to changing market conditions. Resources act as building blocks that enable organisations to realise the previously outlined elements of the DC framework, and its foundation lies in the resourced-based view (Kraaijenbrink *et al.*, 2010; Teece, 2018b). Typically resources are divided into VRIN and ordinary resources (Lin and Wu, 2014). The associated subscale for integrating LM with I4.0 is outlined in Table 10.

The subscale of resources includes the following six items: Dedicating resources to the continuous development of LM and I4.0 (5_6), assembling a core change team based on influence and role-model leadership (5_3), employing external resources for knowledge transfer (5_10), employing external resources in case of lacking own skills (5_9), hire/employ at least one experienced OPEX expert (5_1), and progress reporting should be conducted by process owners (5_11). Participants highlighted the importance of resources dedicated to the continuous development of implemented LM and I4.0 practices, potentially reflecting poorly maintained or 'withering' implementation issues.

4.6. Capabilities

Capabilities determine what a firm can do and how effectively it can make changes (Teece, 2018b). Within the DC framework, two types of capabilities are typically

Table 9. Validated items of Transforming 2: Execution

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
4_26	4.19	4	0.86	1	3.87	Q3	.512	.429	.718
4_19	4.21	4	0.83	1	3.86	Q3	.486	.402	
4_17	3.98	4	0.91	1.75	3.57	Q4	.570	.470	
4_18	3.94	4	0.87	2	3.48	Q4	.567	.465	
4_29	3.79	4	1.05	2	3.18	Q4	.552	.456	
4_27	3.67	4	1.05	1	3.05	Q4	.594	.486	

Table 10. Validated items of Resources

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
5_6	4.49	5	0.73	1	3.99	Q1	.545	.421	.647
5_3	4.40	5	0.80	1	3.76	Q2	.500	.367	
5_10	4.33	5	0.88	1	3.58	Q2	.581	.434	
5_9	4.18	4	0.96	1	3.36	Q3	.456	.365	
5_1	4.17	4	0.92	1	3.20	Q3	.426	.346	
5_11	4.03	4	1.02	1	3.11	Q3	.440	.358	

Table 11. Validated items of Capabilities

Item	Mean	Median	Std.dev	IQR	Rank within scale	Rank across scales	Factor loading	CITC	Cronbach's Alpha
6_4	4.64	5	0.65	1	3.38	Q1	.672	.541	.737
6_5	4.58	5	0.72	1	3.34	Q1	.677	.552	
6_8	4.36	5	0.81	1	2.90	Q2	.603	.515	
6_7	4.42	5	0.73	1	2.88	Q2	.481	.423	
6_6	4.17	4	0.93	1	2.50	Q3	.606	.502	

considered: ordinary and dynamic (Drnevich and Kriauciunas, 2011). With the risk of oversimplification and the intention to distinguish, ordinary capabilities fall into the categories of governance, operations, and administration and relate to how efficiently organisations execute tasks and hence can be considered best practices (Teece, 2014). In contrast, DC determine an organisation's effectiveness, which is about innovating, orchestrating, and adapting (Teece, 2014). In the context of LM and I4.0 integrations, we derived five items forming the subscale of 'capabilities' as presented in Table 11.

The final items of this subscale are: Developing a foundational understanding of LM and I4.0 practices in leadership (6_4), empowering leaders to show openness to new LM and I4.0 practices (6_5), preparing plant managers for new practices through targeted coaching (6_8), training workers in new practices to remain process responsible (6_7), and developing coaching skills in leadership (6_6). Four items of 'capabilities' rank in this framework's first and second quartiles. The fifth item ranks in the third quartile. Hence, the overall relevance of 'Capabilities' potentially plays a higher role.

5. Discussion

Previous research extensively focused on the benefits of integrating LM with I4.0 and recommended practices to consider (Komkowski *et al.*, 2022; Komkowski *et al.*, 2023b). Individual research on LM, I4.0, and DC also contributed to a solid knowledge base concerning concrete implementation strategies for realising potential benefits. For instance, Bortolotti *et al.* (2015) derived a superior sequence for LM implementations, while Kump *et al.* (2018) operationalised concrete practices as DC micro-foundations. This article complements previous research through an integrated perspective of an operational framework that concretises the less researched 'how' level of LM and I4.0 integrations.

The framework consists of 43 concrete practices relating to the five classical dimensions of the DC framework, 'sensing', 'seizing', 'transforming', 'resources', and 'capabilities', and proposes an additional subscale, 'initiating', as a catalyst that triggers the subsequent components of the DC framework. Figure 4 presents an overview of the framework and its subscales. Appendix 2 includes the complete list of each subscale's practices.

The items of 'initiating', like 'visualising target states' (1_7), are designed to generate entrainment effects and provide internal guidance for the subsequent 'sensing' phase. When organisations possess effective 'initiating' capabilities, they are more likely to engage in extensive 'sensing' activities. Consequently, employees are triggered to put into practice the items within the 'sensing' scale, such as seeking 'regular external stimulus' (2_7). Following this increased 'sensing', the organisation can then enhance its 'transforming' capabilities, possibly through approaches like 'focusing on workshop formats' (4_20) or 'nudging digital solutions in improve phases of DMAIC/PDCA' (4_17). Ultimately, the validated items become actionable through 'resources', for instance, by 'utilising external resources for knowledge transfer' (5_10), and 'capabilities', for instance, by 'empowering leaders to demonstrate openness to new LM and I4.0 practices' (6_5).

Throughout the statistical analysis, we confirmed the reliability of each subscale, determining Cronbach's alpha values (Flynn *et al.*, 1994). Four of eight subscales exceed alpha values of .600, representing the minimum level for initial scales, and the second four exceed .700, even fulfilling the thresholds for mature scales (Nunnally, 1978; Forza, 2002; Shah and Ward, 2007). Second, we confirmed convergent validity and unidimensionality of the scales through EFA and discriminant validity determining Fornell Larcker criterion and HTMT ratios (Fornell and Larcker, 1981; Åhlström and Westbrook, 1999; Leoni *et al.*, 2022). This provides tentative evidence that the

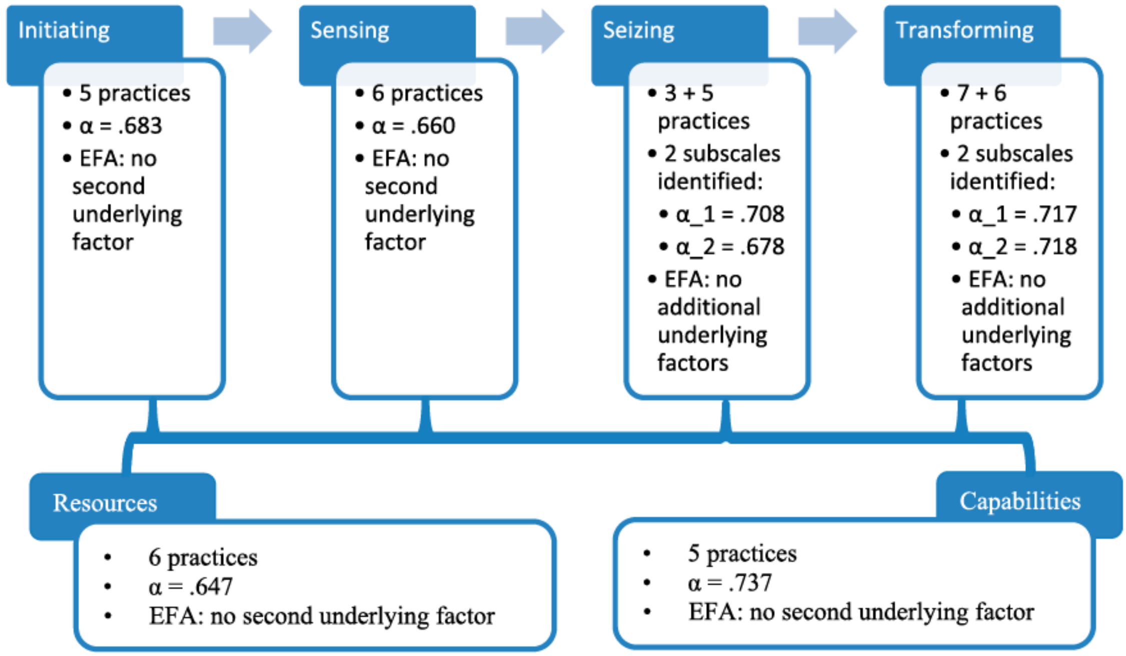

Figure 4. Operational framework for integrating Lean with Industry 4.0. The framework comprises six dimensions: initiating, sensing, seizing, transforming, resources, and capabilities. These aspects are detailed alongside statistical findings related to item quantity, Cronbach's alpha, and outcomes derived from exploratory factor analysis.

presented scales are reliable and valid and invites future research to continue to refine and adapt the proposed scales.

Previous research identified pathways to foster LM or I4.0 integrations through DC. Gutierrez *et al.* (2022) derived that LM implementations foster DC microfoundations, subsequently fostering I4.0 as process innovation. In contrast, Oliveira-Dias *et al.* (2023) propose I4.0 base technologies to improve sensing capabilities by detecting disruptions or waste sources, enhancing LM. On a higher level, these authors propose the implementation of I4.0 or LM to develop DC, which then fosters the integration of the second theme.

Our findings do not contradict these ways of thinking but fall into a different logic. With our framework, we propose to develop DC distinctive for integrating LM and I4.0 without favouring either LM or I4.0 in any integration sequence. Therefore we propose the set of context-specific (LM and I4.0) DC in contrast to Gutierrez *et al.* (2022) or Oliveira-Dias *et al.* (2023), who worked with generic DC. Consequently, the framework offers pathways for firms seeking guidance for concurrent integrations of LM with I4.0 but not neglecting the positive effects if a firm has already integrated either LM or I4.0. In this sense, we support previous research that highlighted moderating effects of previous LM or I4.0 integrations for developing DC and subsequently fostering organisational developments (Felsberger *et al.*, 2020; Tortorella *et al.*, 2021c; Gutierrez *et al.*, 2022; Oliveira-Dias *et al.*, 2023).

At this point, we would like to point out one limitation as our study cannot predict which form of integration is superior, e.g. in relation to performance effects. This aspect has to be addressed as an opportunity for future research.

Following Wilden *et al.* (2013) or Kump *et al.* (2018), previous research concretised items for 'sensing', 'seizing', and 'transforming'. Consequently, the items of 'initiating', 'resources', and 'capabilities' represent novel propositions of this research. Concerning 'sensing', previous research derived several items, such as knowing best practices, current market trends, and how to remain informed (Kump *et al.*, 2018). We confirmed the intention of the 'sensing' scale of employing regular external impulses but derived items that allow companies to shape this capability also by leveraging internal elements, e.g. conducting interviews with staff. As a result, companies do not have to focus exclusively on external stimuli but can draw on a broader base. Concerning 'seizing' and 'transforming' similarly, the focus of our scales is more on offering concrete options for action that support the realisation of items derived by previous research and thus present themselves again at a deeper and more operational level, e.g. supporting derivation and monitoring of improvement initiatives or employing a coaching-based seizing approach.

Furthermore, the state of research on LM and I4.0 integrations strongly focuses on the 'what' level. Case studies typically focus on specific LM practices and I4.0

technologies, most frequently valuestream mapping and simulation (Yilmaz *et al.*, 2022). Our framework differs in that it introduces a model that is able to cover the full range of LM practices and I4.0 technologies depending on organisation-specific requirements. Also, it offers a deeper level of concretisation and proposes a comprehensive set of action-enabling elements (Rossini *et al.*, 2022). Furthermore, by following the logic of DC, the proposed framework is based on a consistency that has been criticised and further developed in the context of organisational development for decades and positions itself as a well-grounded alternative to the use of classic problem-solving techniques (Collis and Anand, 2021; Bueno *et al.*, 2023). Consequently, our research complements previous attempts at deriving integrated constructs for LM and I4.0 integrations. Kamble *et al.* (2020) and Tortorella *et al.* (2021a) derived frameworks linking practices with performance effects. Interestingly, Flynn *et al.* (1994) identified a comparable research focus on performance effects when initially attempting to explicate the operational 'how' level of Quality Management. Therefore, our framework complements previous research on a deeper level, explicitly addressing practices to inform executions of integrating LM and I4.0.

Finally, through our concretisation of DC practices, our findings confirm the high relevance of routines, learning practices, and cultural aspects, with the latter even forming its second-order subscale of the framework (Gutierrez *et al.*, 2022; Csiki *et al.*, 2023).

We derived mean ranks based on Friedman's tests with some noteworthy findings. Items related to governance and execution, which act as the final aspects in a processual perspective of DC, tend to rank lower. Earlier stages of 'initiating', 'capabilities, and 'resources', tend to hold items with higher ranks. We interpret these early practices as leveraging the construct's elements and deciding the inputs' quality for procedurally later DC dimensions. Unfortunately, the present research state is too immature to contrast these findings. Therefore, we suppose a high practical relevance of the presented contribution to fill the empirical and operational research gap in LM and I4.0 integrations (Hines *et al.*, 2023).

5.1. Theoretical implications

Contributions to theory are threefold. Fundamentally, our study provides a methodically robust derivation of 43 concrete practices that characterise the DC components related to the integration of LM and I4.0. This framework aligns with recent calls for more concretisation and exploration at the operational level, akin to micro-foundations, in the realm of DC theory (Schilke *et al.*, 2018; Collis and Anand, 2021; Wu *et al.*, 2023).

Second, in contrast to previous research, which typically focused on established DC components like 'sensing', 'seizing', and 'transforming', we introduce an additional component called 'initiating'. This suggests a targeted approach to preloading and initiating the well-established DC components and challenges the holism and completeness of the DC construct, offering a more nuanced and holistic perspective (Wilden *et al.*, 2013; Kump *et al.*, 2018). Consequently, on the one hand the present paper adds value by confirming and concretising all DC entities in one framework, as shown in Figure 4, while on the other hand proposing a novel component to increase the holism of the construct (Teece, 2018b).

Third, our study confirms the usefulness of employing the DC theory in the context of LM and I4.0 integrations. The framework takes up the core elements of the theory and concretises them. Accordingly, the DC theory has significantly shaped the framework. Consequently, the research contributes to clarifying further contexts where the concept of DC is beneficial (Schilke *et al.*, 2018; Collis and Anand, 2021).

5.2. Managerial implications

Our study showcases several managerial implications. First and foremost, the research provides a practical and actionable framework for managers seeking to integrate LM and I4.0. The 43 validated practices, organised into six subscales, serve as practical checklists and guides for firms to self-assess and adapt their LM and I4.0 integrations. This helps managers move beyond strategic formulation to effective execution (Correani *et al.*, 2020). To the best of the authors' knowledge, the proposed framework is the first to consist of validated scales for LM and I4.0 integrations that are specifically suited for practical implementation and supported by the established DC framework. For example, a management team can use the framework to assess an existing LM and I4.0 integration with regard to the presence of the respective scales' items. The results show potential gaps per integration phase or missing resources or capabilities, which enables a conscious correction avoiding blind spots.

Second, the findings highlight the critical importance of 'initiating' and 'change', as well as 'resources', and 'capabilities' in the integration process. Managers are advised to invest considerable effort in these early stages to set a strong foundation for successful LM and I4.0 integration, which aids in strategic planning and resource allocation as they may involve extensive preparations and lead times (Hughes and Hodgkinson, 2021). For example, the likelihood of successful outcomes in the later phases of LM and I4.0 integrations can be improved by evaluating one's own resources and capabilities in relation to the items presented, as the study has shown that earlier stages of integration tend to rank higher in importance than execution stages.

Finally, the study underscores the significance of leadership and cultural practices, particularly during the 'initiating' phase, to achieve successful integrations. Managers are encouraged to focus on leadership practices that create entrainment effects, aligning organisational activities and fostering a conducive environment for integration (Rotemberg and Saloner, 2000; Williams and Williams, 2007; Balzer *et al.*, 2019).

6. Conclusion

In conclusion, our research has demonstrated the value of an operational perspective for integrating LM with I4.0, rooted in the principles of DC. Our framework provides a concurrently executable approach, offering firms a practical alternative to traditional, more sequential integration methods. The framework's six subscales, including 'initiating', offer a comprehensive guidance for achieving this integration, with a particular focus on actionable items including previously unvisited scales of resources and capabilities.

The framework comprises 43 practices grouped into six subscales: 'initiating', 'sensing', 'seizing', 'transforming', 'resources', and 'capabilities'. The first being a novel proposition to the well-established DC theory generating entrainment effects for the intended integration. Through the use of statistical tests, the practices were validated as a scale, reliable for future research and practitioners to understand what each stage of the framework encompasses; and prioritised, which makes it possible to understand the most important items in each subscale. Our research findings also shed light on the challenges faced during LM and I4.0 transitions. Through Friedman's test rankings, we observed that earlier stages tend to rank higher than the stages of execution (transforming), which may help further understand and prevent low success rates in these transitions. Consequently, firms can benefit in two ways, either using the framework to evaluate their existing integration efforts or as a vehicle to holistically design the setup for an integration of LM with I4.0.

To ensure a clear understanding of the scope and applicability of our findings, it is important to acknowledge the limitations of our study. As an exploratory survey, the development of a new field of research has to be balanced with the established requirements of sample sizes and generalisability (Flynn *et al.*, 1994). Although the sample size of 256 participants is comparable to the average in OM, it remains small, especially in comparison to the number of items (Tortorella *et al.*, 2019; Gutierrez *et al.*, 2022). Furthermore, as already described, the sample is primarily focussed on experts from large German manufacturing firms. Even though it was randomly sampled as part of a master list, a purposive element characterises the sample. The characteristics of the German industry, including its technological advancement and cultural context, potentially influenced our findings such as the prominent role of the early integration phases. As a result, generalisations of our research findings to less technologically advanced countries, different firm sizes, differing LM and I4.0 maturities or cultures with substantial differences should be reflected in future research. Furthermore, we demonstrated that the derived scales are reliable and valid, but further advancements and refinements are necessary to increase alpha values above .80, as Nunnally (1978) suggested.

Second, as methodological constraints, the study employed a cross-sectional design, which restricts the ability to infer causality. Longitudinal studies are recommended to better understand the temporal dynamics and causal relationships. Additionally, self-reported data was used, which may introduce response biases. Incorporating objective measures and triangulating data sources could provide more robust findings.

Third, DC act as the exclusive theoretical lens and thus influence the data collection. Other theoretical lenses, such as contingency or systems theory, or the consideration of multiple theories, typically introduce additional variables and increase holism, which, however, would have further worsened the sample size ratios in view of the exploratory state of research.

Consequently, future research opportunities in the field of LM and I4.0 integrations can reflect contingencies of industries and firm characteristics in cross-cultural and cross-industry comparisons to understand the framework's adaptability, explore alternative theoretical lenses to increase the framework's holism, enhance the reliability and validity of the scales by expanding sample sizes, and draw a link from the presence of items to performance effects. Doing so potentially contributes to an increased understanding of differences in competitiveness and performances related to integrating LM with I4.0 (Schilke *et al.*, 2018; Buer *et al.*, 2021). Besides that, explicitly investigating the differences in organisational performance resulting from the integration type and the role of human factors by conducting a comparative study of sequential vs. concurrent integrations of LM and I4.0, would increase the quality of decision-making. These research directions promise to enrich our understanding of LM and I4.0 integrations, the cross-context applicability, and the impact on organisational performance. The actionable framework developed in this study requires further validation through methodologies such as design science research, action research, or multiple case studies across diverse settings. These settings should include both large and small organisations, as well as sectors such as manufacturing, service, and the public sector, to refine and customise the framework effectively. In the next phase of this study, we aim to validate and enhance the framework through rigorous examination across multiple contexts and organisational sizes.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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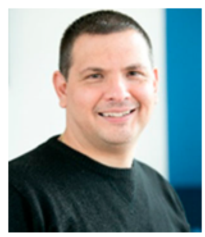

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix 1: Interview guide

NO.	QUESTION:	OPTIONAL FOLLOW-UPS	CATEGORY
1	AGE? POSITION IN COMPANY? YEARS OF EXPERIENCE IN TRANSFORMATIONS, LEAN MANAGEMENT, INDUSTRY 4.0?		OPENING
2	WHAT IS YOUR EXPERIENCE IN INTEGRATING LEAN AND INDUSTRY 4.0?	WHAT HAVE YOU DONE/CHANGED TO EXECUTE THE INTEGRATION?CSBARLINE WHAT KIND OF GOVERNANCE SHOULD FIRMS APPLY? CSBARLINE WHAT KIND OF RESOURCES HAVE BEEN INVOLVED?CSBARLINE WHAT KIND OF CAPABILITIES HAVE BEEN INVOLVED?CSBARLINE WHAT KIND OF PROCESSES HAVE BEEN INVOLVED?	INTEGRATION THEMES
3	HOW SHOULD FIRMS INITIATE THEIR START IN INTEGRATING LEAN AND INDUSTRY 4.0?		
4	HOW CAN FIRMS ADJUST OR DEVELOP THEIR RESOURCES AND CAPABILITIES FOR EXECUTING AN INTEGRATION?		
5	HOW CAN FIRMS IDENTIFY THE RIGHT THEMES OF LEAN AND INDUSTRY 4.0 TO START WITH?	SHOULD FIRMS FOCUS FIRST ON ORGANISATIONAL ASPECTS, NETWORK OF FLOWS, SINGLE VALUE STREAMS OR SPECIFIC PROCESSES?	MODES OF ACTION
6	WHICH ELEMENTS OF INDUSTRY 4.0 SHOULD BE DEPLOYED SEPARATELY TO LEAN?	WHICH ELEMENTS OF LEAN SHOULD BE DEPLOYED SEPARATELY TO INDUSTRY 4.0?	
7	DO YOU KNOW EXAMPLES, WHERE NO PREVIOUS LEAN IMPLEMENTATION IS REASONABLE?	DOES ORGANISATIONAL CULTURE INFLUENCE THE NEED OF A PREVIOUS LEAN IMPLEMENTATION?	
8	DOES THE ROLE OF CHANGE MANAGEMENT CHANGE?	WHICH CHANGES ARE ESPECIALLY RELEVANT WHEN INTEGRATING LEAN WITH INDUSTRY 4.0?	
9	HOW CAN FIRMS GOVERN AN INTEGRATED TRANSFORMATION?	HOW DO YOU THINK ABOUT THE FOLLOWING STATEMENT: LEAN TYPICALLY UTILISES PROBLEM SOLVING TECHNIQUES, INDUSTRY 4.0 TENDS TO ADOPT SCRUM-PROJECTS.	
10	INTEGRATION OF I4.0 INCREASES TECHNOLOGICAL COMPLEXITY; HOW CAN ORGANISATIONS KEEP CONTINUOUSLY LEARNING?		SPECIFIC KNOWLEDGE GAPS
11	WHICH TYPE OF PROCESS STANDARDISATION IS REQUIRED?	HOW CAN STANDARDISATION E.G. BY WORKING INSTRUCTIONS OR PROCESSES BECOME AGILE TO ALLOW FAST ADAPTATIONS?	
12	HOW DO YOU CONSIDER THE ROLE OF EXTERNAL KNOWLEDGE (CONSULTANCIES, UNIVERSITIES ETC.)?		
13	ARE THERE IMPORTANT ASPECTS, THAT WERE NOT MENTIONED, YET?		ENDING

Appendix 2: Item and name of items Matrix

	Item	Text
Initiating	1_2	Joint development of a convincing change strategy by the management team
	1_3	Training of managers in the identification of waste/improvement potentials
	1_5	Establish internal benchmarks for specific Lean and I4.0 practices
	1_6	Develop long-term guiding principles as guidelines
	1_7	Visualise target states (e.g. pictures of a pilot area)
Sensing	2_1	Focus on the vision/target state of a company
	2_10	Regular reflection of own approaches
	2_2	Defining, communicating and breaking down a vision
	2_3	Conducting interviews with staff
	2_4	Focus on high motivation for change among the employees involved
	2_7	Regular external stimulus
Seizing 2	3_10	Seizing LM practices primarily in a coaching-based approach
	3_2	Focus reporting on demonstrating results on the ground
	3_3	Inclusion of management for solving hurdles
	3_4	Involve one level of hierarchy higher than affected areas
	3_5	Initiation of a broad and open communication of progress
Seizing 1	3_6	Develop a key performance indicator system that enables derivation and monitoring of projects
	3_7	Each project should be guided by an easily measurable goal
	3_8	Facilitate transparency on status and progress through reporting apps (e.g. BI reporting)
Transforming 1	4_1	General aspects of good change management remain relevant
	4_2	Feedback channels should be opened to promote/maintain continuous development
	4_20	Focus on workshop formats that involve all people required to evaluate and change a process
	4_24	Allow operational staff to review new practices at regular intervals
	4_4	Increased transparency through digitalisation should be used to communicate successes
	4_6	Required attitudes/values of digitalisation should be specifically developed (e.g. agility, iterative approach, data-based decision-making)
	4_9	The role model function of managers should be actively used (e.g. do not request printouts)
Transforming 2	4_17	Nudging digital solutions in improve phases of DMAIC/PDCA
	4_18	Developing a responsibility-oriented decision-making and accountability system
	4_19	Develop a KPI set that covers the relevant variables of the entire value stream
	4_26	Employing a coaching-based implementation approach
	4_27	Use alternating implementation steps between LM and IT (e.g. LM optimises processes while IT develops digital capabilities for those processes)
	4_29	Training a broad mass in the use of LM and I4.0 change blueprints
Resources	5_1	Hire/employ at least one experienced OPEX expert
	5_10	Employing external resources for knowledge transfer
	5_11	Progress reporting should be done by process owners
	5_3	Assemble a core change team based on influence and role-model leadership
	5_6	Dedicate resources to the continuous development of LM and I4.0
	5_9	Employing external resources in case of lacking own skills
Capabilities	6_4	Developing a foundational understanding of Lean and I4.0 practices in leadership
	6_5	Empowering leaders to show openness to new Lean and I4.0 practices
	6_6	Develop coaching skills in leadership
	6_7	Train workers in new practices to remain process responsible
	6_8	Prepare plant managers for new practices through targeted coachingss