**The integration of Industry 4.0 and Lean Management:  
A systematic review and constituting elements perspective**

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**Abstract**

This paper explores the prevalent themes for integrating Industry 4.0 and Lean Management to provide a red thread concerning ‘what’ and ‘how’ to execute their integration. Furthermore, gaps in current literature are identified, and an agenda for future research is developed. The research is based on a systematic literature review of 111 papers that were published in academic journals between 2015 and 2021. In contrast to previous reviews, we focus on constituting elements of Lean Management and Industry 4.0 to offer a perspective closely related to practical implementations. The findings suggest Total Productive Maintenance as one exemplary constituting element representing the ‘what’ level and Change Management as a discipline with answers concerning the ‘how’ level.The paper offers a holistic view for practitioners facing the need for an integrated implementation of Industry 4.0 and Lean Management. Prevalent themes can be included in organisational transformation efforts to increase success rates in change projects.Deriving gaps in the current literature and developing an agenda for future research focused on operational concepts offers possibilities for further research with high practical relevance.

**Keywords:** Industry 4.0, Lean Management, Operational Excellence, Transformation, Systematic Literature Review

**Paper type:** Literature review

# 1. Introduction

As a low-tech approach, Lean Management (LM) focuses on waste elimination and value creation from customers’ perspectives ([Hopp and Spearman, 2020](#_ENREF_23)). In contrast, Industry 4.0 (I4.0) introduces high-tech approaches through multiple innovations in soft- and hardware ([Lu, 2017](#_ENREF_28)).

Currently, only a small percentage of manufacturing companies address all significant components of LM, and firms are still tethered to LM transitions ([Correani *et al.*, 2020](#_ENREF_9)). Hence, the current task is to integrate both manufacturing paradigms rather than managing singular transformations ([Buer *et al.*, 2021](#_ENREF_3)). Publications concerning LM and I4.0 integrations have increased dramatically since 2015 ([Buer *et al.*, 2018](#_ENREF_4)). Nevertheless, previous research is limited in that it focuses on target dimensions, explicated elements of LM and I4.0 integrations, and primarily derived separated implementation frameworks, less explicating how firms may realise these benefits ([Rosin *et al.*, 2020](#_ENREF_37); [Buer *et al.*, 2021](#_ENREF_3)).

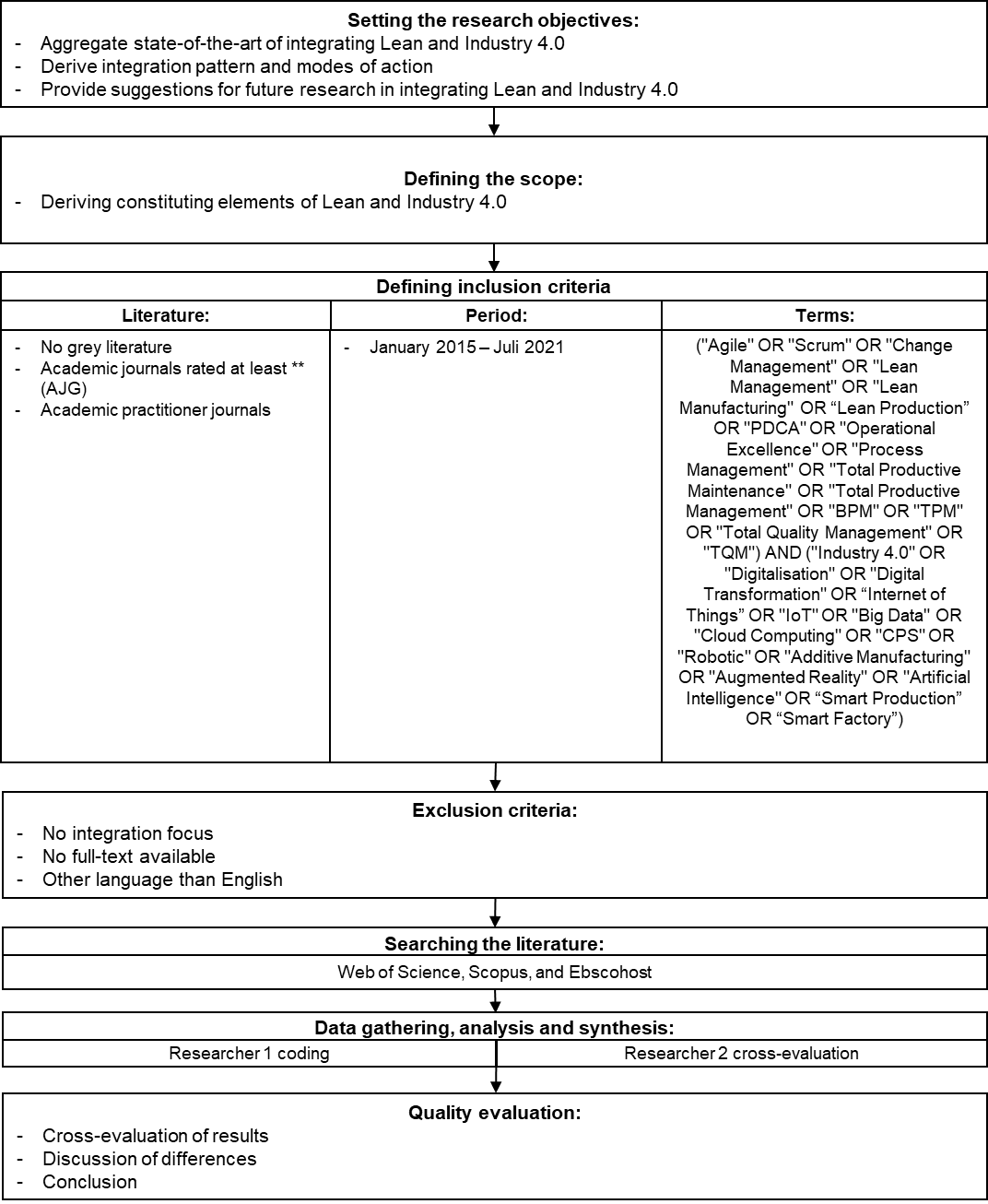
Consequently, the limitations of current research concern the “how” level of explicating modes of action and actual integration practices ([Ding *et al.*, 2021](#_ENREF_13); [Tortorella *et al.*, 2021b](#_ENREF_42)). To address this knowledge gap and contribute in enabling firms to execute integrations of LM and I4.0, this research intends to draw a line from constituting elements (“what” level) to modes of actions (“how” level) by applying a systematic literature review (SLR) ([Tranfield *et al.*, 2003](#_ENREF_43)). Research questions are (1) how can firms execute an integration of LM and I4.0, and (2) which capabilities, resources, and processes are required to execute the integration. Therefore, this research evaluates literature from the start of this research stream in 2015 to 2021 published in Web of Science, Scopus, and Ebscohost on the “what” and “how” level of both manufacturing paradigms. This is a novelty to previous SLR, offering a more operational perspective regarding practical executions. By applying the SLR steps and quality-related selection criteria, a final sample of 111 articles is considered. The results contribute through a holistic perspective concerning the “what” and “how” level of integrating LM with I4.0.

The remainder of this paper is organized as follows. The research approach used in this study is described in section 2. The substance of chosen publications is summarised in section 3. Section 4 discusses the literature review findings and suggests future research topics. The conclusions are presented in section 5.

# 2. Methodology

This paper applies an SLR methodology based on [Thomé *et al.* (2016)](#_ENREF_40) and [Tranfield *et al.* (2003)](#_ENREF_43). Figure 1 summarises the applied SLR process.

Figure 1. SLR process ([Tranfield *et al.*, 2003](#_ENREF_43); [Thomé *et al.*, 2016](#_ENREF_40))



In the first step, a clear statement of research objectives based on the research questions was defined ([Tranfield *et al.*, 2003](#_ENREF_43); [Thomé *et al.*, 2016](#_ENREF_40)). Following the targeted level of integration, this research intends to aggregate the knowledge base in integrating LM with I4.0, considering the level of constituting elements. Furthermore, as a novel contribution, this SLR explicates the body of knowledge concerning how integrations can be executed by identifying integration patterns as modes of action.

As a second step, the scope of the review was defined. In contrast to previous SLR, which approached this topic on a higher level, this paper reflects the interest in revealing a deeper layer of operational integration patterns by considering constituting elements of LM and I4.0 ([Danese *et al.*, 2018](#_ENREF_11); [Ding *et al.*, 2021](#_ENREF_13)). Concerning LM, previous research established measures and bundles ([Shah and Ward, 2007](#_ENREF_39); [Bortolotti *et al.*, 2015](#_ENREF_2)). Total Quality Management, Just in Time, Total Productive Maintenance (TPM), and Human Resources Management aspects are cross-evaluated elements of LM ([Galeazzo and Furlan, 2018](#_ENREF_17)). Following [Lu (2017)](#_ENREF_28), I4.0 is defined as a manufacturing process that is integrated, adaptable, optimised, service-oriented, interoperable, and linked to algorithms, big data, and sophisticated technologies. In detail, constituting elements of I4.0 are defined as cloud computing, cyber-physical systems (CPS), robotics, additive manufacturing, augmented reality, industrial internet of things, and artificial intelligence ([Pacchini *et al.*, 2019](#_ENREF_32)).

In a third step, the scope was transferred to inclusion and exclusion criteria in accordance with previous research. Initial search terms were defined as the previously introduced elements of LM and I4.0. Potentially, this falls into the idea of [Buer *et al.* (2018)](#_ENREF_4), who considered constituting elements of I4.0. Through the literature search, 2.646 articles were identified as published in academic journals between January 2015 and July 2021. This time frame can be considered appropriate as publications fulfilling the inclusion and exclusion criteria were not published before within the considered academic databases of Ebscohost, Scopus and Web of Science. The screening process was informed by the defined inclusion and exclusion criteria and cross-evaluated through a text-mining categorisation algorithm. This leads to a final sample of 111 articles considered for full-text review.

In a fourth step, data gathering, analysis and synthesis were conducted. During the full-text review, classical variables as key research topics, methodology, country, industry, and specific variables, e.g. integration type, informed data gathering. For coding, NVivo was used and cross-evaluated by a second researcher. Based on the coding, articles were clustered according to their origin, e.g. TPM. Based on the coding, results were contrasted within the established clusters to achieve the research objectives.

# 3. Literature Review

## Literature characteristics

This subsection presents the characteristics of the literature in integrating LM with I4.0.

The research field has emerged since 2016. While figure 2 visually indicates breaking the rising trend due to the end of article selection in July 2021. We expect a persisting trend of rising publications, being aligned with the rising interest in this future-proof theme ([Chiarini *et al.*, 2020](#_ENREF_6)).

Figure 2. Publications per year

The rising trend is driven by contributions from Italy, Germany, Brazil, India, the UK, and Portugal, which account for 56% of published articles in 2021. Articles published from the USA offer a peak in 2019, explaining the fourth rank compared to other contributing countries.

Figure 3. Publications per country

Publications in this research field are fragmented. Only seven authors published more than one article, with one author being the most prolific with five publications. In contrast to the matured field of LM research, prolific authors strongly influence publication rates, which currently explains the top contributing position of Brazil, which deviates from previous analyses of research trends. The following table lists the most prolific authors and their current research focus.

Table 1. Prolific authors

| Primary authors | Article count | Topics |
| --- | --- | --- |
| Tortorella G. | 5 | * LM automation framework * I4.0 and LM production implementation * Operational Excellence's role in the I4.0 era * Comparison of manufacturers from developing and developed economies |
| Yadav N. | 2 | * Impact of I4.0, Lean Six Sigma (LSS), and quality management systems on organisational performance * Critical success factors for LSS in quality 4.0 |
| Sony M. | 2 | * LSS design of CPS architecture for I4.0 * I4.0 and LM integration |
| Buer S.-V. | 2 | * Effects of LM and I4.0 on operational performance * I4.0-LM relationship |
| Mishra S. | 2 | * Automation's human and process characteristics * Automation's technological dimensions |
| Chiarini A. | 2 | * Integration of LSS and I4.0 * Integration of I4.0, quality management, and TQM |
| Ghobakhloo M. | 2 | * Strategic principles for digital transformation success * LM-digitised manufacturing |

Regarding the landscape of journals, this SLR identified publications from 51 journals, while 29 journals account for 80% of publications. The three most prolific journals are International Journal of Production Research (11%), TQM Journal accounting (6%), and Journal of Manufacturing Technology Management (5%).

Figure 4. Publications per journal

## Research methodologies

This subsection synthesises the applied research methodologies. While the authors applied a wide range of methodologies, 80% of the present research is built on literature reviews (29%), case studies (29%), and surveys (23%).

Table 2. Research methodologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Methodology** | **Mixed methods** | **Qualitative** | **Quantitative** | **Theoretical** | **Sum** |
| Literature Review |  |  |  | 33 | 33 |
| Case Study |  | 32 |  |  | 32 |
| Survey | 2 |  | 23 |  | 25 |
| Interviews |  | 5 |  |  | 5 |
| Mixed Methods | 2 | 1 | 1 |  | 4 |
| Simulation |  | 1 |  | 1 | 2 |
| Action research |  | 2 |  |  | 2 |
| Case Study, Action Research |  | 2 |  |  | 2 |
| Delphi technique |  | 1 |  |  | 1 |
| Focus groups |  | 1 |  |  | 1 |
| Text mining |  |  | 1 |  | 1 |
| Grounded Theory |  | 1 |  |  | 1 |
| Ethnography |  | 1 |  |  | 1 |
| ISM |  | 1 |  |  | 1 |
| **Sum** | **4** | **48** | **25** | **34** | **111** |

Due to the current exploratory research status, a majority of qualitative investigations could be expected. Case studies typically drive this phase of research. Nevertheless, the high amount of surveys and literature reviews seems surprising in contrast to findings singularly derived from recent developments of LM, e.g. in service or healthcare, or I4.0 in general as a more recent research field ([Danese *et al.*, 2018](#_ENREF_11); [Piccarozzi *et al.*, 2018](#_ENREF_34)).

## Themes of integration

This subsection aggregates the findings of the SLR process. General considerations concerning the “what” level are presented within the subsection of LM as a paradigm. Subsequently, the TPM and Change Management (CM) subsections represent the “what” level of exemplary constituting elements.

#### 3.3.1 Lean Management as a paradigm

A significant research stream considers LM a paradigm of Operations Management ([Hopp and Spearman, 2020](#_ENREF_23)). This subsection aims to aggregate research that is focused on LM as a paradigm. The prevalent themes within this research stream are I4.0 leverages LM, a balanced consideration, and LM as a prerequisite.

Table 3. Integration of LM with I4.0

| Research stream | Core arguments | Exemplary contributions | Knowledge gaps |
| --- | --- | --- | --- |
| I4.0 leverages LM | Established LM journeys are positively impacted by integrating specific I4.0 elements | [Rosin *et al.* (2020)](#_ENREF_37); [Pagliosa *et al.* (2021)](#_ENREF_33) | Examine influence on the entire organisation and all levels of value chains;  Examine impact of I4.0 on industrial systems and impact on less prevalent themes of health and safety, collaboration, and teamwork |
| Balanced consideration | I4.0 and LM are synergetic - an integrated implementation makes one and one more than two | [Ding *et al.* (2021)](#_ENREF_13); [Vlachos *et al.* (2021)](#_ENREF_44) | Extend research beyond pilot/conceptual level; Determine which I4.0 and LM elements are loosely connected, allowing for concurrent implementation |
| LM as a prerequisite for I4.0 | Robust and waste-free processes as a foundation established by LM increase likelihood of successful I4.0 transformations | [Buer *et al.* (2018)](#_ENREF_4); [Buer *et al.* (2021)](#_ENREF_3); [Tortorella *et al.* (2021b)](#_ENREF_42) | Examine how technologies affect implementation strategies and LM organisations; Examine connections between individual LM/I4.0 elements; Investigate practical combination of both paradigms |

Regarding the I4.0 leveraging LM research stream, authors conclude that the application of I4.0 technologies boosts the potential impacts of LM, and there is widespread consensus that I4.0 improves an organisation's LM capabilities ([Rosin *et al.*, 2020](#_ENREF_37)). The literature base includes various case studies for I4.0 elements leveraging LM concepts and approaches ([Davies *et al.*, 2017](#_ENREF_12); [D'Orazio *et al.*, 2020](#_ENREF_10); [Pagliosa *et al.*, 2021](#_ENREF_33)). These case studies demonstrate the transfer from kanbans to e-kanbans, more reliable data for quality control, and the shift from Value Stream Mapping (VSM) as a snapshot to continuous and real-time VSM ([Anosike *et al.*, 2021](#_ENREF_1)). Furthermore, deployments proved the positive interaction of robots conducting high-accuracy and repeatability processes while operators execute more flexible operations ([Rey *et al.*, 2021](#_ENREF_36)). Finally, cybersecurity, cloud, and horizontal/vertical integration are underrepresented within this research stream ([Rosin *et al.*, 2020](#_ENREF_37)). In contrast, horizontal/vertical integration and cloud services have previously been identified as critical components of effective I4.0 integrations ([Frank *et al.*, 2019](#_ENREF_16); [Pagliosa *et al.*, 2021](#_ENREF_33)). Hence, this might be one of the drawbacks of using I4.0 to exploit LM rather than incorporating I4.0 holistically. To summarise, this research stream appreciates I4.0 for its transformative potential, and it may show that I4.0 applications do not need prior LM implementations. For example, an organisation might deploy e-kanbans or big data-based quality control as a state-of-the-art practice independently of LM maturities.

Instead of unilaterally considering the integration of LM or I4.0, the stream of a balanced consideration developed a bidirectional supportive impact of LM or I4.0 ([Ding *et al.*, 2021](#_ENREF_13)). The authors of this camp confirmed that LM plays a mediating function in I4.0. However, the leveraging impact of I4.0 is also underlined, and the authors advise that organisations merge both paradigms to become smart and lean ([Kamble *et al.*, 2020](#_ENREF_25)). Furthermore, organisations may remove LM hurdles by adopting I4.0 elements, such as supplier integration and development, or Just-in-Time, which can be strengthened by IIoT, big data analysis, sensors, and other I4.0 elements. As a result, LM systems are upgraded to become part of an LM virtual manufacturing network, which shares both tangible and intangible resources ([Kamble *et al.*, 2020](#_ENREF_25)). Financial restrictions, insufficient managerial support, limited awareness, hesitant behaviour, and a lack of capabilities were identified as integration barriers ([Kamble *et al.*, 2020](#_ENREF_25)). In contrast, [Westerman *et al.* (2019)](#_ENREF_45) found that I4.0 has a supportive influence in building unique cultural practices to boost learning speed and level, indirectly addressing the learning aspect of LM. To summarise, the authors respect the mediating function of LM but prefer to evaluate both paradigms equally and encourage the inclusion of socio-technical thinking within an LM culture ([Vlachos *et al.*, 2021](#_ENREF_44)).

Finally, the third stream considers LM a prerequisite, with organisations that have previously adopted LM having a better chance of incorporating I4.0 ([Anosike *et al.*, 2021](#_ENREF_1)). The foundation to be created before integrating I4.0 is the execution of basic LM principles as derived by [Shah and Ward (2007)](#_ENREF_39) or, more broadly, a specific level of LM maturity ([Rybski and Jochem, 2021](#_ENREF_38); [Tortorella *et al.*, 2021a](#_ENREF_41)). The likelihood of effective I4.0 integrations rises as LM maturity rises. LM processes may be further optimised with I4.0 technology, making a digital transition easier ([Buer *et al.*, 2018](#_ENREF_4)). LM is the central Operational Excellence (OpEx) theme ([Tortorella *et al.*, 2021a](#_ENREF_41)). This guarantees that unproductive operations are not digitalised or automated adhering to previously agreed automation norms ([Buer *et al.*, 2021](#_ENREF_3)). LM maturity introduces success factors: a learning culture, senior management leadership, inter-functional team development, change governance frameworks, and training activities ([Buer *et al.*, 2021](#_ENREF_3); [Pozzi *et al.*, 2021](#_ENREF_35)).

Finally, the three primary research streams developed empirical and qualitative/quantitative data to support their guiding ideas. The development of capabilities and, as a result, the prevention of hurdles by prior LM journeys for easier I4.0 integrations cannot be overlooked ([Buer *et al.*, 2021](#_ENREF_3); [Pozzi *et al.*, 2021](#_ENREF_35)). Simultaneously, research introduced I4.0 applications that do not require previous LM implementations ([D'Orazio *et al.*, 2020](#_ENREF_10); [Anosike *et al.*, 2021](#_ENREF_1)). As a result, the balanced examination of LM and I4.0 appears to combine both perspectives and possibly optimise value for organisations that must implement both transformative changes simultaneously ([Ding *et al.*, 2021](#_ENREF_13)).

#### 3.3.2 Total Productive Maintenance

TPM is defined as a methodology to increase existing equipment’s availability and holds a long tradition in OpEx research ([Chan *et al.*, 2005](#_ENREF_5)). The impending integration of TPM with I4.0 has gained prominence in the last decade, and viable techniques have emerged ([Tortorella *et al.*, 2021b](#_ENREF_42)). This SLR derives three themes: data collecting and predictive techniques, planned and autonomous maintenance, and sophisticated technology applications.

Table 4. TPM and I4.0 integration

| Integration theme | Core arguments | Exemplary contributions | Knowledge gaps |
| --- | --- | --- | --- |
| Data collecting and predictive techniques | Predictive models or neural networks; human-machine interface (HMI), IIoT, and CPS; sensors, wireless sensor networks, middleware, and interconnectedness | [Davies *et al.* (2017)](#_ENREF_12); [D'Orazio *et al.* (2020)](#_ENREF_10); [Anosike *et al.* (2021)](#_ENREF_1); [Fernandes *et al.* (2021)](#_ENREF_15) | Using artificial intelligence technology (i.e., machine learning) to allow machines to learn from data and anticipate what will happen next;  Dealing with complicated techniques may need substantial training |
| Planned and autonomous maintenance | Smart devices, network connectivity, digital maintenance calendars, retrofit capability, interoperability and orchestration capability, CPS, HMI, | [Kolberg *et al.* (2017)](#_ENREF_26); [D'Orazio *et al.* (2020)](#_ENREF_10) | Improve understanding of how to integrate new technology into architecture;  Dealing with complicated techniques may need substantial training. |
| Sophisticated technology uses | Cloud, AR | [D'Orazio *et al.* (2020)](#_ENREF_10); [Fernandes *et al.* (2021)](#_ENREF_15); [Pagliosa *et al.* (2021)](#_ENREF_33) |

Data collection, which will be accomplished by sensors, wireless sensor networks, middleware, and interconnectivity, can help achieve the goal of breakdown reductions ([Anosike *et al.*, 2021](#_ENREF_1)). [Davies *et al.* (2017)](#_ENREF_12) put this idea into practice, stating that sensors identify components needing replacement or oil replenishment and provide signals to maintenance workers or operators in planned maintenance events ([Davies *et al.*, 2017](#_ENREF_12)). This improves maintenance precision, as evidenced by various contributions ([D'Orazio *et al.*, 2020](#_ENREF_10)). Furthermore, if fed to predictive models, the massive data collection enhances predictive maintenance techniques, increasing the precision of machine health assessments and allowing maintenance personnel to respond before breakdowns occur ([D'Orazio *et al.*, 2020](#_ENREF_10)). In contrast, other authors emphasise HMI, IIoT, and CPS integration for predictive techniques ([Pagliosa *et al.*, 2021](#_ENREF_33)). Vibration analysis, ultrasound, thermography, voltage, dynamic pressure, and visual inspections were identified as the most promising factors in predictive maintenance by [Fernandes *et al.* (2021)](#_ENREF_15). Nonetheless, these data are available without I4.0 integration, but they become more accurate and dependable if available in real-time ([Fernandes *et al.*, 2021](#_ENREF_15)).

The second subtheme of scheduled maintenance benefits from I4.0 integration in monitoring, control, conduction, and automated computation and classifications ([D'Orazio *et al.*, 2020](#_ENREF_10)). Furthermore, the implementation of maintenance calendars becomes more transparent and dependable. Machines can automatically offer information about necessary maintenance operations ([D'Orazio *et al.*, 2020](#_ENREF_10)). These technologies may be retrofitted to older machines, resulting in increased interoperability and orchestration capability ([Kolberg *et al.*, 2017](#_ENREF_26)). On the other hand, autonomous maintenance may be improved by using CPS and HMI to monitor fundamental conditions, such as dirt sources and lubrication sites, and signalling to operators ([D'Orazio *et al.*, 2020](#_ENREF_10)). Smart gadgets that visualise maintenance calendars/activities or coach operators through these operations might further enhance this ([D'Orazio *et al.*, 2020](#_ENREF_10)). Furthermore, abnormal circumstances may be signalled from machines to operators, and when integrated with predictive models, machines can learn from previous abnormal conditions to predict the likelihood of reoccurrence ([D'Orazio *et al.*, 2020](#_ENREF_10)). Qualitative research confirms the viability of these techniques; nevertheless, real-world case studies proving automated and AI-based maintenance applications are scarce ([Chiarini and Kumar, 2020](#_ENREF_7); [Fernandes *et al.*, 2021](#_ENREF_15)).

To summarise, TPM benefits significantly from adding data collection and maintenance operations that can improve accuracy and perhaps decrease or eliminate unexpected failures ([D'Orazio *et al.*, 2020](#_ENREF_10); [Fernandes *et al.*, 2021](#_ENREF_15)). Currently, TPM builds strongly on technical research rather than explicating soft elements or modes of action in terms of how improvements can be practically realised. As a result, gaining a better knowledge of how to put the presented principles into practice will improve the practical worth of future contributions.

#### 3.3.3 Change Management

CM can be defined as a process of continuous renewal of firms’ capabilities, structures, and directions ([Moran and Brightman, 2001](#_ENREF_30)). This subsection focuses on CM's role in integrating LM with I4.0. The elements and stages of change, comprehensive CM models, and success factors are the three themes deduced from the articles recognised by this SLR.

Table 5. CM and I4.0 integration

|  |  |  |  |
| --- | --- | --- | --- |
| Integration theme | Requirements | Exemplary contributions | Knowledge gaps |
| Change management phases and elements | Transformation strategy, design, delivery, governance and leadership | [Mugge *et al.* (2020)](#_ENREF_31) | Models require further investigation and empirical validations |
| Change management models | Change readiness of individuals and organisations, suitability of structures, processes, competencies, and capacities; participation, development, information, and security | [Kadir and Broberg (2020)](#_ENREF_24); [Gfrerer *et al.* (2021)](#_ENREF_19); [Hizam-Hanafiah *et al.* (2021)](#_ENREF_22) | Longitudinal case studies;  Combination of quantitative and qualitative data;  Developing a better knowledge of the transition to I4.0;  Examine transformation frameworks and approaches to dealing with readiness perceptions and developments. |
| Success factors | Internal/external focus, collaboration, readiness evaluations, and DC components | [Ghobakhloo and Iranmanesh (2021)](#_ENREF_20); [Machado *et al.* (2021)](#_ENREF_29) | Quantitatively assess the importance of success determinants; Empirical validations |

Concerning elements of change, [Mugge *et al.* (2020)](#_ENREF_31) statistically identified essential issues to be covered in integrating I4.0: transformation strategy, design, delivery, governance, and leadership. Furthermore, [Machado *et al.* (2021)](#_ENREF_29) experimentally created a model for change in I4.0 integrations that partially validates and expands on these features and includes the phases: 1) creating a vision, 2) identifying reasons for change, 3) building a company strategy and value proposition, 4) aligning the leadership team, 5) selecting sources to conduct the change, 6) analysing difficulties and investments, and 7) designing KPI to track the change. In contrast to these overarching change elements and phases, several authors derived change models focusing on details and requirements for success. In comparison, [Kadir and Broberg (2020)](#_ENREF_24) focus on activities in three phases, from readiness/preparation through post-change, [Gfrerer *et al.* (2021)](#_ENREF_19) statistically derived activities necessary for change preparedness. Finally, [Hizam-Hanafiah *et al.* (2021)](#_ENREF_22) suggested a model with a greater degree of abstraction.

The fundamental aspects of change readiness are contrasted in the following table.

Table 6. Change readiness aspects in I4.0 integrations

| [Kadir and Broberg (2020)](#_ENREF_24) | | [Gfrerer *et al.* (2021)](#_ENREF_19) | [Hizam-Hanafiah *et al.* (2021)](#_ENREF_22) |
| --- | --- | --- | --- |
| Well-being | Performance | Overall | Overall |
| Individuals' knowledge levels | The maturity and readiness of an organisation to deal with digital solutions | Management preparation, proper organisational structure, and the availability of managers with digital expertise | Process preparedness, as well as organisational change readiness |
| Clarity on the implications on present roles, responsibilities, and duties | Stakeholders' and workers' level of support and buy-in | Willingness to adapt proactively, innovative culture, and economic resources | Change commitment, change leadership, and people preparedness |
| Job safety | Employees' current IT abilities and their ability to develop new ones | The availability of required competencies, understanding of readiness perceptions | Individual aversion to change |
|  |  | Employees’ early involvement |  |

Building on change readiness, previous research derived essential elements during a change, which are contrasted in the following table.

Table 7. Change management aspects in I4.0 integrations

| [Kadir and Broberg (2020)](#_ENREF_24) | | [Gfrerer *et al.* (2021)](#_ENREF_19) | [Hizam-Hanafiah *et al.* (2021)](#_ENREF_22) |
| --- | --- | --- | --- |
| Well-being | Performance | Overall | Overall |
| Continual information flow | New solution knowledge and comprehension |  | Change management |
| Employee participation | | Employee empowerment and participation in initiatives |
| Meaningful consideration of the division of labour between workers and digitalisation | Employee skills and competencies being trained and updated | Internal and external capabilities and resources must be built, integrated, and reconfigured by organisations. |
| New digital solutions' design and maturity | |  |

Finally, post-change elements are considered important for sustainability in change, which is contrasted in the following table.

Table 8. Post-change aspects in I4.0 integrations

| [Kadir and Broberg (2020)](#_ENREF_24) | | [Gfrerer *et al.* (2021)](#_ENREF_19) | [Hizam-Hanafiah *et al.* (2021)](#_ENREF_22) |
| --- | --- | --- | --- |
| Well-being | Performance | Overall | Overall |
| The dedication of management and  resources | | / | |
| Standard operating procedures, training materials | Dependence on new digital technologies |
| Evaluation of physical and cognitive ergonomics | Positive development of changes |
| Job safety |  |

In conclusion, [Gfrerer *et al.* (2021)](#_ENREF_19) defined two types of dimensions that explicitly describe organisational assets, processes, and activities being ready for the intended state of change, concluding that individual beliefs, competencies, and shared beliefs must be addressed. In contrast, other authors incorporate more emotional characteristics, such as job stability or clarity about the consequences of change, yet most of the elements remain comparable. Finally, [Kadir and Broberg (2020)](#_ENREF_24) stress the need to add an after-change phase for overall well-being and success.

Finally, the research discusses success determinants and barriers. [Machado *et al.* (2021)](#_ENREF_29) developed specific sources for leveraging change and challenges/success factors. This contrasts with the qualitative findings of [Ghobakhloo and Iranmanesh (2021)](#_ENREF_20) and is summarised in the following table.

Table 9. Sources, challenges and success determinants

|  |  |  |
| --- | --- | --- |
| Category | [Machado *et al.* (2021)](#_ENREF_29) | [Ghobakhloo and Iranmanesh (2021)](#_ENREF_20) |
| Sources | Internal workshops and events, benchmarking, consulting services, and I4.0 readiness evaluations | External digitalisation assistance, digitalisation readiness evaluations, and strategic planning |
| Challenges/success determinants | Time, data quality, digital knowledge and skills, governance frameworks, culture, and top management support | Resource availability, management expertise, business partner preparedness, CM expertise, IT knowledge, cybersecurity maturity, and IT and technology readiness |

Finally, both contributions offer equivalent sources of change, albeit highlighting either internal or external assistance differently. The authors agree on resource and competency needs regarding challenges/success determinants. Furthermore, [Machado *et al.* (2021)](#_ENREF_29) focus on governance structures and culture. In contrast, [Ghobakhloo and Iranmanesh (2021)](#_ENREF_20) apply a more technical view considering cybersecurity and technological readiness and take a more technical approach to cybersecurity and technology preparedness.

## Modes of action

Research starts to understand the modes of action and how firms adapt their processes and routines, which are required to integrate LM with I4.0 ([Buer *et al.*, 2021](#_ENREF_3)). Findings from each prevalent integration cluster are aggregated to present the knowledge base of modes of action.

Based on the articles covered by this SLR, four clusters were identified with relevance to how integrations can be executed: Implementation strategies, barriers, success factors, and capabilities/resources/processes. The following table aggregates these findings.

Table 10. Modes of action

| Cluster | Core content |
| --- | --- |
| Implementation strategies | Value stream orientation, problem-solving techniques (e.g. PDCA), initial LM implementation, concurrent implementation of LM and I4.0, point-based I4.0 implementation, waterfall project management, CM approaches, agile, and pilot-based approaches |
| Barriers | Financial constraints, poor management support, low awareness, reluctant behaviour, digitalisation or automation of wasteful activities, technological complexity introduced to shopfloor processes hinders involvement, lack of resources and competencies (time, data quality, digital knowledge and skills, governance structures) |
| Success factors | Cultural and behavioural change, top management support/leadership, development of inter-functional teams, employee involvement and empowerment, training, development,  process changes without extensive coding capabilities, balance between modelling of processes and flexibility, reliable and efficient data management systems, resources for data gathering and storing, high computational power, clarity about change impact and job security, management competency, business partner readiness, CM competency, IT expertise, cybersecurity maturity, IT and technology readiness, employees’ level of information, budget |
| Capabilities/ Resources/ Processes | Organisation: Innovation/continuous improvement culture, data-driven decision making, supportive learning environment and leadership style, change governance structures, employee awareness, organisational structures of agility, adaptability, ambidexterity, increased communication from and to workers  Resources: Processes for automatic data gathering and analysis, light touch processes, infrastructural ﬂexibility, profound and modelled business processes (e.g. BPMN V2), processes for balancing exploration and exploitation, network integration, retrofit ability, interoperability and orchestrate-ability of machines, preparation/availability of digitally experienced managers, workforce transformation, developing internal consultants, cross-functional understanding and team composition  Capabilities: I4.0 technologies/digitalisation, data science, coding, complex and data-based problem solving, operationalisation of algorithms in operations/processes, process/data mining, simulation, IT security, data protection, advanced production technologies, modern interfaces, processes for integrating/reconfiguring internal and external competencies and resources, readiness of people, processes and technologies |

The aggregation of integration modes of actions offers an overview of applied methodologies for implementation, involved resources and capabilities. Concerning implementation models, currently, no presented model is agreed upon in the literature, and most models reflect first understandings ([Tortorella *et al.*, 2021a](#_ENREF_41)). By contrasting these individual models, one can conclude an iterative procedure as being most widely applied at the most basic level of academic agreement. This means firms tend to mature from beginner to intermediate to advanced integration status, and involved technologies are grouped according to these maturing levels, e.g. [Tortorella *et al.* (2021a)](#_ENREF_41) or [Rybski and Jochem (2021)](#_ENREF_38). Concrete implementation sequences require empirical validation compared to established models, e.g. sand cone model for LM implementation ([Bortolotti *et al.*, 2015](#_ENREF_2)).

Additionally, present research evaluated resources and capabilities and most agreed seems to be the lack of managerial and personnel digital expertise ([Gfrerer *et al.*, 2021](#_ENREF_19)). This shows a natural logic, as firms have been involved for decades in LM transformations and might relate to the critical finding that I4.0 hinders people's involvement through its technological complexity. Nevertheless, pathways for overcoming this integration barrier require further exploration and research-derived initial variables for further elaboration.

Case studies of I4.0 transitions confirmed the role of enabling mechanisms, resource and capability building, and strategic coherence ([Grandinetti *et al.*, 2020](#_ENREF_21); [Ciasullo *et al.*, 2021](#_ENREF_8)). Previous research reflecting the integration of LM with I4.0 referred to the theory of Dynamic Capabilities (DC), which builds on these elements to explain how integrations may be executed ([Garbellano and Da Veiga, 2019](#_ENREF_18); [Felsberger *et al.*, 2020](#_ENREF_14)). Hence, we refer to the DC framework to place our findings in an overall context. In that sense, developing capabilities and resolving barriers function as foundational modes of action, while an iterative implementation strategy that includes success factors executes an integration. This should be accomplished with continuous adaptations and improvements of these two interrelated steps. Figure 5 outlines this process and intends to serve as a starting point for further in-depth explorations in subsequent studies.

Figure 5: Initial integration process



# 4. Discussion and future research

This SLR intends to aggregate the “what” and “how” of integrating LM with I4.0 to enrich the literature base with specific references for practitioners facing the challenge of executing an integration. First, the number of articles published considering the integration of LM with I4.0 has dramatically increased on the level of constituting elements since 2015, with 111 articles covered within this SLR, while [Buer *et al.* (2018)](#_ENREF_4) built on 23 articles from 2014 to August 2017. These numbers prove the growing relevance for academics and industry.

Second, the findings from this SLR draw a link from integration themes to modes of action. This operational perspective is a novel contribution that intends to enable actual change, which cannot be achieved without addressing the how level. Additionally, it follows recent calls for research by aggregating the knowledge base of the operational integration level ([Rosin *et al.*, 2020](#_ENREF_37); [Buer *et al.*, 2021](#_ENREF_3); [Ding *et al.*, 2021](#_ENREF_13)).

In reflection on constituting elements of LM, the significant elements are covered by integration research ([Shah and Ward, 2007](#_ENREF_39); [Bortolotti *et al.*, 2015](#_ENREF_2); [Hopp and Spearman, 2020](#_ENREF_23)). In contrast, constituting elements of I4.0 show a tendency to cover involved technologies and a lack of evaluating the role of enterprise architectures and horizontal/vertical integration ([Frank *et al.*, 2019](#_ENREF_16); [Yli-Ojanperä *et al.*, 2019](#_ENREF_46)). This finding is critical due to its prominent role in I4.0 transformations and underrepresented reflection in current research ([Liao and Wang, 2021](#_ENREF_27)).

Third, while academic research covered much ground in explicating the “why” and “what” of integrating LM with I4.0, contributions especially targeting the how-level, remain sparse. On a higher level, [Rosin *et al.* (2020)](#_ENREF_37) linked LM practices to I4.0 capability levels and concluded leveraging effects for LM practices if combined with specific I4.0 practices. In that sense, the mode of action is to deploy I4.0 to strengthen LM. Consequently, firms following this logic implement LM first. Anyhow, firms cannot pause the fourth industrial revolution until an LM implementation matures ([Buer *et al.*, 2021](#_ENREF_3)). On a deeper level, other authors derived modes of actions applying specific perspectives, e.g. the role of process management within TPM and I4.0 integrations or specific resource/capability adaptations to overcome increasing technological complexity ([Fernandes *et al.*, 2021](#_ENREF_15); [Ghobakhloo and Iranmanesh, 2021](#_ENREF_20)). Nevertheless, success potentially depends on integrating these specific perspectives into more holistic ones, as this SLR intended. The explicated clusters for pathways of concurrent integrations can be understood as a step toward this direction. However, the literature base only starts to elaborate on concrete implementation boundaries and models ([Tortorella *et al.*, 2021a](#_ENREF_41)).

Finally, the main knowledge gaps identified by this SLR are summarised in the following table.

Table 11. Future research opportunities

|  |  |  |
| --- | --- | --- |
| Focus | Gap/limitation | Future research opportunities |
| What | Pilot/lab status; Not all essential constituting elements covered yet, e.g. role of enterprise architectures | Expand research status; Fully explore the integration of LM and I4.0 on the level of its constituting elements; Include soft aspects |
| How | Lack of operational concepts/frameworks for integration, including and linking modes of action; Lack of generalisation | Explore implementation sequences, derive concrete modes of action potentially linked within one framework, including involved, processes, resources, and capabilities |

# 5. Conclusion and limitations

This SLR reviews the integration of LM and I4.0. A link is drawn between “what” themes firms should integrate and “how” integrations might be executed. The findings indicate that integrations cover the essential constituting elements of LM. However, the role of enterprise architectures and horizontal/vertical integration as part of constituting elements of I4.0 are less reflected. Regarding how firms can execute, serious gaps were identified concerning operational concepts and pathways. Initial contributions evaluate the role of resources, capabilities, and implementation models, but detailed evaluations of enabling processes, routines, and favourable implementation sequences require further explication and evaluation.

This study contributes to theory by providing a holistic view of the integration of LM and I4.0. Second, by explicating resources, capabilities, and further aspects of how integrations can be executed as a foundation for further research. This can be considered by future explorative research through related theoretical lenses, e.g. Dynamic Capabilities. Practically, this study introduces a novel view of a red thread from “what” to “how” firms can execute integrations. Practitioners can use these characteristics inside their integration procedures to boost the chance of success based on the aggregated modes of action.

There are several limitations of this study. First, because of the selected search terms and databases, potentially valuable studies remain uncovered. Second, only English literature published in high-ranking and practitioner journals was considered. Additionally, due to the focus on integrating LM and I4.0, only academic papers considering both paradigms were considered, and transferable insights from research focused either on LM or I4.0 were not part of this SLR. Finally, we can introduce the practical orientation by exemplary themes, further constituting elements should be reviewed to offer additional red lines from “what” to “how”.

Due to the apparent knowledge gaps, the authors intend to contribute through a mixed-methods study targeting pathways of manufacturing firms executing simultaneous integrations.

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