

Lean Industry 4.0: Past, present, and future

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ABSTRACT

This paper employs a real-time, open-question qualitative survey method to investigate the past, present, and future of the Lean Industry 4.0 field. A major trend is found in researchers moving from technological backgrounds such as engineering, or other STEM subjects, into more socio-technical departments and developing interests in wider areas such as people, supply chain, and sustainability. A holistic perspective of the field is presented including a call to commonise the researcher-favored term “Lean Industry 4.0.” An inclusive and detailed definition of Lean Industry 4.0 takes into account the different survey responses. A wide range of future research gaps is identified within the context of a first-of-its-type future research framework.

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Introduction

During the last four decades manufacturing companies have faced an increasingly volatile and competitive environment with growing market demands (Gligor and Holcomb 2012; Lestari, Marie, and Sari 2021; Lu and Xu 2018) calling for emerging concepts and technologies. Two of the most important of these have been “Lean” and “Industry 4.0,” which have recently been combined in the literature usually as either “Lean Industry 4.0” (Arey, Le, and Gao 2021) or “Lean 4.0” (Rosin et al. 2022).

Lean production has its origins in the Japanese automotive industry and Toyota in particular (Holweg 2007). It aims to improve the flow within value streams by eliminating waste, improving quality and productivity and meeting or exceeding customers’ expectations (Womack, Jones, and Roos 1991). *Industry 4.0*, as a term, has its origins at the 2011 Hannover Fair with a presentation given by Siegfried Dais (Bosch) and Henning Kagermann (Acatech). It is intended to apply the principles of Cyber-Physical Systems (CPS), internet and future-oriented technologies and smart systems within an enhanced human-machine interaction paradigm (Sanders, Elangeswaran, and Wulfsberg 2016).

There has been much confusion in industry, and debate in the academic literature, about how these two approaches might fit together as they have similar aims in terms of increasing manufacturing productivity (Rüttiman and Stöckli 2016). This is partly because *Lean* is usually considered to be a low-tech approach which excels with its simplicity (Dickmann 2008) whereas *Industry 4.0* is highly technology-driven and hence might be less than appealing to some Lean advocates (Pagliosa, Tortorella, and Ferreira 2021). There have been several recent papers calling for research in this area (Sanders, Elangeswaran, and Wulfsberg 2016; Buer, Strandhagen, and Chan 2018; Rossini et al. 2019) as there was, at the time, no comprehensive framework connecting the two (Kolberg and Zühlke 2015; Leyh, Martin, and Schäffer 2017). The favored methodology for this research is through either quantitative industry surveys (Tortorella, Giglio, and van Dun 2019; Buer et al. 2021) or literature reviews (Cattaneo et al. 2017; Bittencourt, Alves, and Leão 2021; Ejsmont et al. 2020; Kipper et al. 2020; Núñez-Merino et al. 2020; Pagliosa, Tortorella, and Ferreira 2021; Elafri, Rose, and Boudemagh 2022; Stojanović 2022).

However, this earlier research has only taken us so far forward and there is a call for further research,

particularly into how many scientists are dealing with the topic; what countries/organizations are represented by the authors (Ejsmont et al. 2020; Elafri, Rose, and Boudemagh 2022), theoretical models (Bittencourt, Alves, and Leão 2021; Ejsmont et al. 2020), inter-disciplinary research (Stojanović 2022), and empirical validation of successful integration (Pagliosa, Tortorella, and Ferreira 2021).

This paper seeks to further the research in the area of *Lean Industry 4.0* by reviewing the topic's past, present, and future. In particular, there will be a focus on the future agenda and a framework for this for researchers. Understanding the past background of researchers and their current interests will also help predict the future as well as possible problems in achieving it (Potter et al. 2011; Goss, McNutt, and Bible 2021).

Specifically, the following research questions will be addressed:

- RQ1 – *What is the background of the key researchers working in the Lean Industry 4.0 field?*
- RQ2 – *What is the present profile of key researchers working in the Lean Industry 4.0 field?*
- RQ3 – *What are the interests of the key researchers within the field of Lean Industry 4.0?*
- RQ4 – *How do the key researchers define the topic of Lean Industry 4.0?*
- RQ5 – *What do the key researchers see as the gaps within the Lean Industry 4.0 field that need to be addressed in future research and how might these be addressed?*

Method

As mentioned above, much of the recent research into *Lean Industry 4.0* is in the form of quantitative industry surveys or literature reviews. The former provides an opportunity to assess the current position of a medium-large sample of industrial respondents as well as provide potentially statistically significant results. However, such surveys are often restricted to a limited geographical area, making generalization hazardous (Tortorella, Giglio, and van Dun 2019; Buer et al. 2021). They may also suffer from bias due to how the sample has been obtained (Guide and Ketokivi 2015), sample members known to the authors might be more likely to respond, or answers may be exaggerated due to social desirability (Buer et al. 2021).

Literature reviews are helpful to readers as they summarize a large amount of material and can provide a structured, repeatable, and scientific process (Núñez-Merino et al. 2020). However, they are by

their nature past-oriented and may miss newer material that has not yet been published in journals. They also may not convey the evolutionary nature of research (Ejsmont et al. 2020), are subject to missing data as not all indexes are used (Núñez-Merino et al. 2020) and may apply subjective criteria for the selection of articles and the classification of research input into pre-defined coding schemes (Ejsmont et al. 2020). Of particular concern is the widespread use of this method in *Lean Industry 4.0 research* potentially leading to repetition and inward reflection.

In this research, the authors chose to use a *novel qualitative survey method* with key global researchers in the field of *Lean Industry 4.0*. This was done to take the best out of surveys and literature review methods whilst avoiding some, but not all, of the pitfalls. We are not seeking to discredit other methods, but more to suggest that heterogeneity of research approaches allows for new research lenses and together with triangulation with previous research provides both validation and extension opportunities.

A *qualitative open questions method* was chosen due to the nature of the research questions and to allow for clear and comprehensive responses (Creswell 2014) including unforeseen answers, particularly from an academic sample likely to want to express their views in words (Royal Literary Fund 2022). This method can also allow for a wide geographical sample and importantly allows for real-time responses to the questions rather than time-lag information received from literature searches. The sample was designed to be as inclusive and inter-disciplinary as possible taking into account the wide-ranging scope of the subject of *Lean Industry 4.0*. It also allowed for data to be collected about the past, present activities and future views of the respondents.

Research stages

In common with *systematic reviews*, the authors have sought to develop a protocol, extract data and synthesize the resulting information (Tranfield, Denyer, and Smart 2003; Macpherson and Holt 2007). This has been achieved through the application of a ten-stage approach consisting of a Google Scholar initial loop, before an Academic Survey loop (see Figure 1). This allowed for summary data to be gained on the complete sample set before detailed data from the respondent community. This approach, therefore, provides both breadth and depth of coverage.

1. *Search Strategy* – This activity aimed to establish how data would be obtained including the

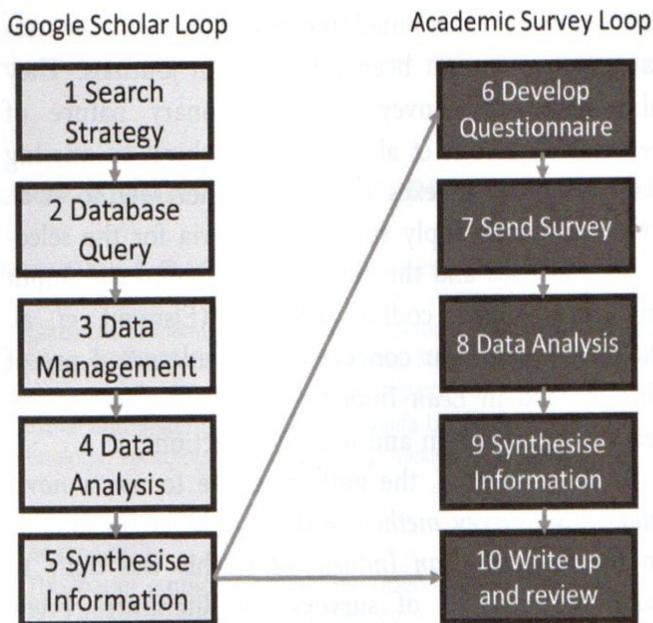


Figure 1. Research Stages.

mechanics of search and retrieval (Ferenhof and Fernandes 2016). Due to the nature of this study, and following Pagliosa, Tortorella, and Ferreira (2021), the keywords defined were “Lean” and “Industry 4.0.” Google Scholar was chosen as the database because it has very wide inter-disciplinary coverage not found in other academic databases (Ruths and Al Zama 2010). Such nonrandom sampling is a popular approach to studying recent phenomena (Saurin et al. 2020; Tortorella et al. 2021). The purpose here was to gain as broad a coverage as possible.

2. *Database Query* – The Google Scholar database was searched in early 2022. Filters were applied to only include peer-reviewed articles without limiting the dates of publication with keywords found in the title and/or the text. This yielded a total of 9,510 articles. The authors of these articles were then individually searched to identify the key authors in the field. A key author was defined as someone who had published one or more peer-reviewed articles including the terms *Lean* and *Industry 4.0* and had a substantial citation publication record. Hence, this would include authors who have a track record in an established area, such as *Lean*, and might only have recently published in the “Lean Industry 4.0” realm.

The citation record is a widely held performance criterion for academics (Nagaoka 2006). A cutoff point for the initial data capture was set at 1,000 citations, although this was later extended to the top 300 global authors as this community was very close to this Figure (921 citations as of April 2022 being the actual cutoff). Three

authors were excluded for ethical reasons. This citation Figure shows the academic’s work has received a good reach and is a point at which saturation of coverage might be achieved (Ruths and Al Zama 2010). Such a sample base is unusually large and comprehensive for a qualitative survey (Sharoff 2008; Shetty 2018). Taking the 300 authors together, their work had received a total of 1,541,178 citations.

The location of each of the 300 key authors was recorded together with the first (of up to 5) word(s) or phrases that they had entered into Google Scholar to describe their area of interest. Restricting this to the first entry was to ensure the reliability of the data and reduce bias as some authors had only recorded one interest area.

3. *Data Management* – This activity involved the organization of the data so that it could be later filtered and analyzed. This was done through a series of pages in excel.
4. *Data Analysis* – This stage supported the identification of relevant aspects related to the research topic (Ferenhof and Fernandes 2016). The analysis took two parts. First, analyze the geographical location of the author by country and continent. Second, identify clusters of interest. Such clustering or bundling is a well-established approach within research into both *Lean* (MacDuffie 1995; Shah and Ward 2003) and *Industry 4.0* (Götz and Jankowska 2017; Suleiman et al. 2022). Due to the nature of the topic, helicopter view clustering (Suleiman et al. 2022) was employed using the judgment of one of the authors and validated through review by the other authors (Miles and Huberman 1994).
5. *Synthesize Information* – At this stage, the information from the previous stages was synthesized into a series of tables and Figure which will be displayed and discussed below.
6. *Develop Questionnaire* – The questionnaire was developed to gain the views of the sample academic community on the Research Questions (Appendix). It was kept as succinct as possible to maximize the response rate.
7. *Send Questionnaire* - It was sent by email using Google Forms to the 300 academics together with one follow-up email two weeks after the first contact. In total 87 responses were received (29%) which might be considered high for surveys, being well above the 20% suggested by Kelley et al. (2003) or the multi-disciplinary

academic average of 55.6 found by Baruch (1999). Attention was also directed to identifying any bias in terms of more/less cited authors and geographical responses to ensure coverage of the respondents' was reasonably representative. The respondents collectively had a total of 419,998 citations (27% of the total population). In terms of geographical spread, this varied by continent from 25% to 47% with the two largest respondent continents, Europe and Asia at 27%. These results meet the representative criteria set out by Qualtrics (2022).

8. *Data Analysis* – Content analysis was applied, as it refers to the categorization, tagging, and thematic analysis of qualitative data combining the analysis results with behavioral data for deeper insights (Mayring 2004). Content analysis of transcripts was conducted to verify communication patterns in a replicable and systematic manner (Bell, Bryman, and Harley 2018), generating a narrative for analysis. This content analysis helped deal with latent interpretations' intricacies and identify latent concepts (White and Marsh 2006). Excerpts from the transcripts were utilized to code potential insights. We utilized words and short phrases as labels to code the data and examine different topics and associations between them (Hsieh and Shannon 2005). Codes were then sorted into categories based on how different and associated they were, organizing findings into meaningful information blocks. Furthermore, the data was analyzed using excel into the researchers' past activity (undergraduate degree studied and location), present focus (current location, department, preferred definition of the subject, current interests and industry focus) and future focus in terms of gaps they see within the broad *Lean Industry 4.0* area. Using this second method, it was possible to triangulate the results of the area of interest of the 300 key researchers with the 87 respondents who recorded their three main interest areas (a total of 239 as a small number declined to take up all 3 choices). This multi-method approach allowed for a more in-depth real-time view of the respondents and might be regarded as more reliable as the Google Scholar data by its very nature dates from when it was completed at some point in the past.
9. *Synthesize Information* – At this point, the information from the previous stages was synthesized into a series of tables and Figures which will be

displayed and discussed below. It was also possible to develop a framework for a future research agenda.

10. *Write-up and Review* – The last stage was aimed at consolidating and recording the results in line with the Research Questions. Such a comparison allowed us to indicate the main findings of our research (Ferenhof and Fernandes 2016).

Literature review

Lean

The early literature on *Lean* was dominated by the application of tools and techniques, with a major focus on shop floor manufacturing (for instance: Akao 1991; Bicheno 1991) These and other publications largely viewed *Lean* through an industrial engineering lens. Also, *Lean* was seen as about waste removal; indeed the first two sentences of the introduction to the classic text "Lean Thinking" are: "*Muda*. It's the one word of Japanese you really must know" (Womack and Jones 1996:15). At this point there was scant focus on the other two areas of *muda*, *mura*, and *muri*. In the same vein, *Lean* was viewed as a largely operational shop floor manufacturing phenomenon. In Toyota's terms, this would be a focus on *Continuous Improvement* and not the equally important area of *Respect for Humanity* (Monden 1983) which was later termed "Respect for People" (Liker 2004).

Lean is now seen as a socio-technical approach that considers humans as a fundamental factor in improvement (Pagliosa, Tortorella, and Ferreira 2021, Núñez-Merino et al. 2020). It was not until this current century that those within the *Lean* community started to have any real focus on the wider aspects of *Lean* with a realization that the subject had evolved (Hines, Holweg, and Rich 2004), or perhaps the academic community had a firmer grasp what Toyota actually did (Liker 2004). This evolution included:

- A more strategic element of *Lean* such as *hoshin kanri* or strategy deployment (Tennant and Roberts 2000; Witcher 2003).
- A systems perspective (Mann 2009; Martyn and Crowell 2012; Hines and Butterworth 2019).
- A focus on individual and organizational learning (Shook and Womack 2008; Ballé et al. 2010).
- Leadership approaches (Spear 2004; Emiliani 2008).
- As well as behavior (Hines et al. 2008; Mann 2009).

- Which areas are most compatible (Tortorella, Giglio, and van Dun 2019; Buer et al. 2021) and the wider integration of tools and technologies (Tortorella et al. 2020; Elafri, Rose, and Boudemagh 2022),
- The role of people (Romero, Stahre, and Taisch 2019a; Bittencourt, Alves, and Leão 2021; Burggräf et al. 2020), roles and skills (Gallo et al. 2021; Santos et al. 2021; Waschull et al. 2022), learning (Ansari, Erol, and Sihn 2018; Romero et al. 2020) and work conditions (Colim et al. 2021; Lagorio, Cimini, and Gaiardelli 2021; Gao et al. 2022),
- Whether the approach is more applicable in certain industries (Reinhardt, Oliveira, and Ring 2020; Danese, Mocellin, and Romano 2021; Hariry, Barenji, and Paradkar 2022; Sá et al. 2022; Yang et al. 2022) developed/developing countries (Ciano et al. 2021; Pagliosa, Tortorella, and Ferreira 2021) or size of companies (Agostini and Nosella 2019; Kolla, Minufekr, and Plapper 2019), and
- How the approach can be widened further to include other subjects such as Six Sigma (Efimova, Bris, and Efimov 2021; Tissir et al. 2022), sustainability (Bhattacharya et al. 2014; Kabzhassarova et al. 2021; Wuest et al. 2022) the Circular Economy (Awan, Sroufe, and Bozan 2022; Filho et al. 2022) and the Supply Chain (World Economic Forum 2019; Tortorella et al. 2020).

In terms of future gaps and trends, many of the papers have identified one or a small number based on their research findings. Some of the more comprehensive papers are from Buer, Strandhagen, and Chan (2018), Ciano et al. (2021), Ejsmont et al. (2020), and Pagliosa, Tortorella, and Ferreira (2021). Each of these relies, of course, on the views of the respective authors.

Results and discussion

Lean Industry 4.0 – the past

This first section will show the results and discussion around *RQ1* about the background of the key researchers working in the Lean Industry 4.0 field. Previous research studies, based on small samples of past published works, have found that work on *Lean Industry 4.0* predominantly came from Germany with Italy, Poland, USA and China also being important sources (Ejsmont et al. 2020; Pagliosa, Tortorella, and Ferreira 2021). This current research, based on data from Google Scholar, in contrast, found a much more dispersed distribution of sources as shown in Table 1.

Table 1. Distribution of total population and survey respondents by country.

Country	Total Population by Country n = 300	Respondent Population by Country n = 87	Respondent Percentage by Country
Italy	37	11	30%
India	27	5	19%
UK	22	6	27%
USA	22	6	27%
Portugal	21	7	33%
Germany	20	3	15%
Brazil	15	7	47%
Spain	14	5	36%
France	11	5	45%
Malaysia	7	1	14%
Turkey	7	0	0%
Australia	6	1	17%
Austria	6	1	17%
China	6	3	50%
Poland	6	1	17%
Ireland	5	2	40%
South Africa	5	2	40%
Sweden	5	0	0%
Denmark	4	0	0%
Finland	4	1	25%
Hungary	4	2	50%
Greece	3	0	0%
Morocco	3	2	67%
Norway	3	2	67%
Switzerland	3	1	33%
Bangladesh	2	0	0%
Canada	2	2	100%
Chile	2	1	50%
Hong Kong	2	1	50%
Lithuania	2	0	0%
Netherlands	2	1	50%
New Zealand	2	1	50%
Other	20	7	35%

The Top 300 key researchers in the field were drawn from a total of 53 countries with the top ten nations producing 65% of the work and these were in descending order: Italy, India, UK, USA, Portugal, Germany, Brazil, Spain, France and Malaysia. Researchers were spread across all six continents with Europe (188) and Asia (52) being the main sources.

There are several reasons for this different result. First, in this work, the use of Google Scholar allowed for a very inclusive population of multi-disciplinary researchers as Google Scholar covers 80–90% of all articles published in English (Khabsa and Giles 2014) whereas the search engines used by other researchers have a narrower disciplinary focus. This may lead to the exclusion of areas such as construction research. Second, this work has been carried out more recently meaning the research community may have widened. Third, the current research has a different focus in reviewing researchers who have published in the broad *Lean Industry 4.0* area but a large part of their work might be in a more focused area such as *Lean, Industry 4.0* or other wider areas such as supply chain or sustainability. This is both a limitation and a

Table 2. Distribution of total population and survey respondents by continent.

Continent	Total Population by Continent n = 300	Respondent Population by Continent n = 87	Respondent Percentage by Continent
Europe	188	50	27%
Asia	52	14	27%
North America	25	9	36%
South America	17	8	47%
Africa	10	4	40%
Australasia	8	2	25%

strength as a more general community is included. However, on balance, this can be justified as it provides a different viewpoint from other research which has perhaps unveiled new information which might provide insight into highly published authors moving into the *Lean Industry 4.0* field. It could therefore play an important role in helping to predict the future direction of the publication.

As discussed in the method section, this research collected summary data at the total 300 sample level as well as more detailed data from the respondents to the online survey. Of the 300 key researchers, 87 completed the survey, their geographical distribution is also shown in Tables 1 and 2. To identify more about the key researchers, we asked about their undergraduate degrees. The largest part of the group 54 (62%) had an engineering degree, with 10 (11%) having a sector-specific degree, 5 (6%) having a joint management/engineering degree, with 4 (5%) one from each of having a management and computer science degree. There is a considerable body of evidence that suggests that people's mindset is changed and fixed in the introductory period of the undergraduate period of their life (Dai and Cromley 2014; Limeri et al. 2020) This appears to be particularly the case for STEM subjects (Shively and Ryan 2013; Flanigan et al. 2017). Of the 87 respondents, 78 (90%) might be considered to have taken STEM or partially STEM undergraduate degrees. It might be possible therefore to suggest that a large part of the key researchers have a relatively defined technological mindset.

Lean Industry 4.0 – the present

This second section will present the results and discuss RQ2, RQ3, and RQ4 around the present profile of key researchers working in the *Lean Industry 4.0* field, what their specific interests are and how they define the topic

Table 3 compares the undergraduate location of the respondents with their current location. Whilst the location of researchers is relatively stable there are

Table 3. Undergraduate degree location, current location, and net migration of respondent.

Country n = 87	Undergraduate Degree	Current Location n = 87	Net Migration
UK	2	6	4
USA	3	6	3
Canada	0	2	2
Ireland	0	2	2
South Africa	0	2	2
Spain	3	5	2
Australia	0	1	1
Finland	0	1	1
France	4	5	1
Hong Kong	0	1	1
Hungary	1	2	1
Italy	10	11	1
Japan	0	1	1
Luxembourg	0	1	1
New Zealand	0	1	1
Switzerland	0	1	1
UAE	0	1	1
Belgium	1	1	0
Iran	1	1	0
Malaysia	1	1	0
Mexico	1	1	0
Morocco	2	2	0
Netherlands	1	1	0
Norway	2	2	0
Poland	1	1	0
Thailand	1	1	0
Austria	2	1	-1
Bangladesh	1	0	-1
Chile	2	1	-1
China	4	3	-1
Croatia	1	0	-1
Ghana	1	0	-1
Lebanon	1	0	-1
Nigeria	1	0	-1
Pakistan	1	0	-1
Portugal	8	7	-1
Spain and United Kingdom	1	0	-1
Turkey	1	0	-1
Vietnam	1	0	-1
Brazil	10	7	-3
Germany	7	3	-4
India	11	5	-6

some clear trends. First, there appears to be a net migration to some more developed countries, namely the UK, USA, Canada, Ireland, and Spain. This may be explained due to work opportunities as well as the English language of most of these (which dominates the academic literature). A similar position is also found in South Africa which saw inward migration from other less-developed African nations. Second, in contrast, there is an outflow or "brain-drain" from developing countries, in particular India and Brazil. The one other country with out-migration is Germany (to neighboring Austria, and Luxembourg), perhaps due to the spread of the *Industry 4.0* subject from Germany and the ease of movement within the EU.

Table 4 illustrates the summary of the current departments of the respondents with 41 in engineering, 19 in management, 14 in management/engineering and 6 in sector-specific (all bar one in

Table 4. Departmental distribution of respondents.

Department Grouped n = 87	No.	Department Detail n = 87	No.		
Engineering	41	Industrial Engineering/Automation	18		
		Mechanical Engineering	11		
		Engineering and Science	5		
		Production Engineering	2		
		Intelligent Systems Science and Engineering	1		
		Structural Mechanics	1		
		Engineering and Mineral Resources	1		
		Department of Engineering for Innovation	1		
		Science & Technology	1		
		Management	19	Business/Management	19
			Management/Engineering	14	Production and Operations Management
		Operations, Logistics and Supply Chain Management		3	
		Management and Engineering		2	
Mechanics, Mathematics and Management	1				
Industrial Ecosystems	1				
Technology & Operations Management	1				
Economics, Engineering, Society, and Business Organization	1				
Sector	6	Construction/Civil Engineering	5		
		Food Technology and Biotechnology	1		
Information Technology	1	Business Informatics Processes and Systems	1		
Education	1	Education	1		
Engineering/Sector	1	School of Engineering and Architecture	1		
Information Technology	1	Information and Knowledge Management	1		
Decision Analytics	1	Decision Analytics and Risk	1		
Advanced Study	1	Advanced Study	1		
Industry	1	Industry	1		

Table 5. Undergraduate degree subject of respondent.

Undergraduate Subject Grouped n = 87	No.	Undergraduate Subject Detail n = 87	No.
Engineering	54	Mechanical Engineering	17
		Industrial Engineering	11
		Production Engineering	6
		Engineering	2
		Automation Engineering	1
		Electronic Engineering	1
		Engineering	1
		Chemical Engineering	1
		Control and Automation Engineering	1
		Electrical and Electronics Engineering	1
		Electrical Engineering	1
		Electronics Science	1
		Electrotechnical Engineering	1
		Hybrid genetic algorithms for a multiple-objective scheduling problem	1
		Industrial and Manufacturing	1
		Industrial Electronics	1
		Industrial Engineering and Management	1
		Industrial Management	1
		Manufacturing Engineering	1
		Materials Engineering	1
		Motorsport Engineering	1
		Production System Design	1
		Sector	10
	Food Nutrition		1
Management/Engineering	5	Management Engineering	4
		Business Engineering	1
Management	4	Business	3
		Organization & Management in Industry	1
Computer Science	4	Computer Science	3
		Information systems for maintenance	1
Economics	3	Economics	1
		Economy and Management	1
		Industrial Economics and Technology Management	1
Lean	2	Lean	1
		Lean Manufacturing	1
Geography	1	Geography	1
Mathematics	1	Mathematics	1
Natural Resources	1	Natural Resources Technology	1
Physics	1	Physics	1
Political Science	1	Political Science	1

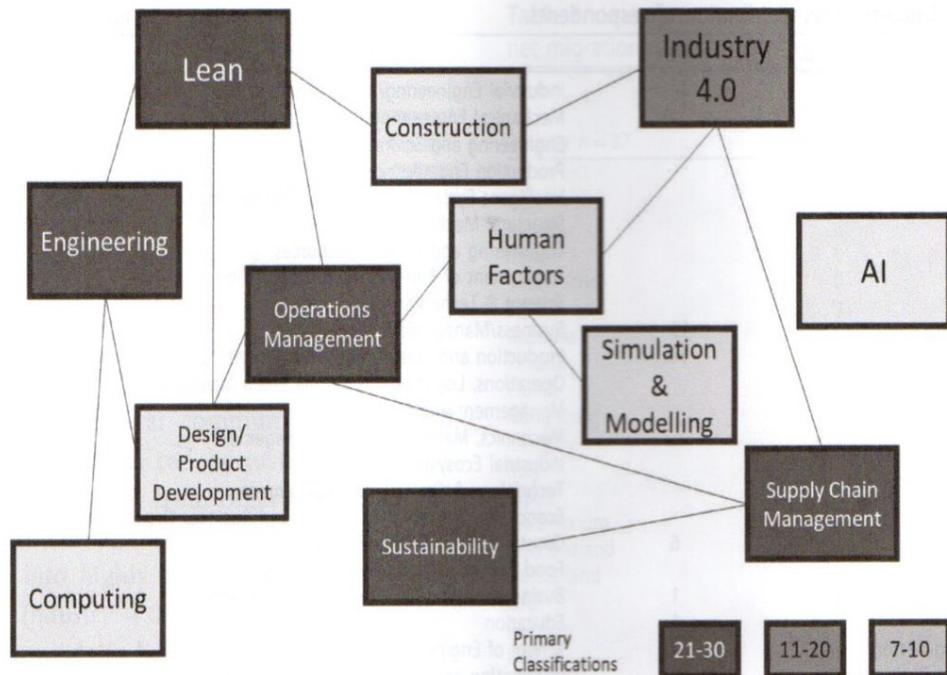


Figure 2. Helicopter Clustering of Researcher Google Scholar Primary Classifications Interests, $n = 300$.

construction or civil engineering departments). The preponderance of engineering is in line with earlier findings by Ejsmont et al. (2020).³ However, there is a much higher number of researchers recorded in this paper from management departments. Many of these appear to have only recently started publishing (as co-authors) in the *Lean Industry 4.0* literature with past backgrounds in the supply chain, sustainability and *Lean* itself (e.g., Saberi et al. 2019; Kamble, Gunasekaran, and Dhone 2020; Danese, Mocellin, and Romano 2021; Reyes, Mula, and Díaz-Madroñero 2021; Hines and Netland 2022; Khan et al. 2022; Sony, Antony, and McDermott 2022; Ullrich, Teichmann, and Gronau 2022). There is one recorded case of a move to industry, with some key researchers also partly working in industry or consultancy.

Comparing this with the data behind Table 5, it is possible to see the following trends. First, there has been a movement from pure engineering departments where undergraduate degrees were taken to management or management/engineering departments. Second, there has been a movement from computing degrees to management departments and third, there has been a movement from construction/civil engineering to management or engineering departments. In summary, the major movement is from technology undergraduate degrees to more socio-technical departments.

The subject interest of the researchers was acquired in two ways. The interest area of the whole key researcher population of 300 was gauged by their first recorded area of interest in Google Scholar which

Table 6. Current research interest groups.

Major Interest Groups $n = 239$	No.
Industry 4.0 Tools & Technologies	39
Sustainability/Circular Economy	34
Industry 4.0/Smart Manufacturing	26
Lean/Lean Manufacturing	23
Supply Chain	16
People, Leadership & Culture	12
Simulation/Modeling/Computation/Data Analytics	10
New Product Development/Innovation	8
Lean and Industry 4.0	8
Construction 4.0	7
Lean Tools	5
Digital/Lean Healthcare	5
Models, Paradigms & Frameworks	4
SME	4
Industry 4.0 and Learning	3
Other	35

might be regarded as their main interest. A summary of this is shown in Figure 2. This has been clustered in a similar way to Götz and Jankowska (2017), Ejsmont et al. (2020) and Suleiman et al. (2022) as this is a popular way to portray the data (Shah and Ward 2003). Six main clusters were found: operations management (27), supply chain management (26), *Lean* – including similar areas such as Lean Six Sigma, Six Sigma and Agile (25), sustainability (21), engineering (21) and *Industry 4.0* (15). Six smaller clusters were also found: artificial intelligence (9), simulation & modeling (8), design/product development (8), computing (8), human factors (8) and construction (7). There are also 100 other responses with 4 or fewer recordings, many of which were specific *Industry 4.0* technologies.

The second method used was the Top 3 areas of interest of the respondents (a total of 239 as a few of

Table 7. Preferred research industry.

Preferred Industry n = 87 (multiple answers)	No.
Any	23
Manufacturing/Industry	20
Automotive/Automotive Components	20
Healthcare	6
Construction/AEC	5
Aeronautics/Aerospace	4
Food & Drink	4
Pharmaceutical/Biopharma	4
Architecture/Civil Engineering/Construction	3
Electrical/Electronics	3
Metal/Metal Forming	3
Industrial Machinery	3
Agriculture	2
Footwear/Textile	2
Discrete Manufacturing	2
ETO/Project-Based Production	2
Engineering	1
Chemical	1
Oil & Gas	1
Service	1
Semi-Process Industry	1
Intelligent Systems	1
Mechanical Industry	1
SME	1
Public Sector	1
Higher Education	1
Rubber Product Industries	1
Smart Manufacturing	1
Smart Logistics	1

the 87 key researchers did not record 3 interests). This was also clustered as shown in Table 6. The largest of the clusters are specific *Industry 4.0* tools and techniques (39), sustainability/circular economy (34), *Industry 4.0* (26), and *Lean* (23). This newer real-time data does show some important differences in clustering with less focus on general terms such as engineering and operations management and more focus on areas such as the circular economy, *Industry 4.0* and people and culture. Drawing concrete conclusions from the differences is dangerous due to the different data sets and the unknown and variable date of Google Scholar data. However, it may be no coincidence that the areas highlighted in the later data are in line with the movement from *Industry 4.0* to *Industry 5.0* (Breque and De Nul 2021).

The respondents were also asked which industry they were interested in studying (see Table 7). This area is not well covered in the literature, apart from the five-paper literature summary from Buer, Strandhagen, and Chan 2018 and in a call for wider research (Elafri, Rose, and Boudemagh 2022). Almost half (43) of the respondents appeared to be general in their interest in recording any manufacturing/industry. Apart from this, the industries most mentioned were automotive (20), healthcare (6), construction (5), aerospace (4), food & drink (4) and pharmaceuticals (4). Such a concentration on the automotive sector is not surprising bearing in mind the origins of *Lean* (Womack, Jones, and Roos

Table 8. Preferred topic terminology.

Preferred Topic Terminology n = 87	No.
Lean Industry 4.0	30
Lean 4.0	17
Industry 4.0	7
Lean Automation	3
Digital Lean	2
Digital Lean Manufacturing	2
I4.0	2
Intelligent Lean	2
Lean	2
Lean Manufacturing	2
Smart Manufacturing	2
4th Industrial Revolution	1
Digital Operations	1
Digital Supply Chain	1
Digitalization and Intelligentisation of Production Systems	1
Smart Lean Manufacturing	1
Lean Industry	1
Intelligent Systems for Industry 4.0	1
Lean & Industry 4.0	1
Lean Construction 4.0	1
Lean Digital	1
Lean in Industry 4.0	1
Lean Smart Manufacturing	1
Lean Transformation	1
Legile	1
OPEX4.0	1
Don't agree with the concept	1

1991). These sectors are all well-researched in both *Lean* (Danese, Manfè, and Romano 2018) and *Industry 4.0* (Tasmin et al. 2020). However, traditional sector definitions within *Lean Industry 4.0* are now becoming blurred providing opportunities and challenges for researchers (Li et al. 2021).

The last area of investigation for the present period is the terminology and definition of the topic we have termed *Lean Industry 4.0* here (see Table 8). There were a large number of ideas although *Lean Industry 4.0* with 30 and *Lean 4.0* with 17 were by far the most cited along with just *Industry 4.0*. The remaining suggested terminologies tended to be synonyms of *Lean Industry 4.0* with terms such as supply chain, manufacturing or operations replacing *Lean* and terms such as intelligent, smart, or digital replacing the term *Industry 4.0*. It is therefore suggested that the term *Lean Industry 4.0* be used in the research community.

The most problematic area in the research was searching for a definition. This is not surprising as *Lean Industry 4.0* is the combination of two subject areas that both have no commonly agreed definition. Of the 87 respondents, two suggested that it was not sensible to combine the two areas and the others suggested a definition of *Lean Industry 4.0* or their preferred terminology. A selection of the more detailed definitions is given in Table 9. As can be seen, these were quite diverse as each researcher provided a perspective guided by their own particular interest such as *Lean*, Supply Chain, *Industry 4.0*, or Digital Twin.

Table 9. A selection of respondents' definitions of Lean Industry 4.0 or their preferred terminology.

Preferred Terminology	Definition
Lean Industry 4.0	A cluster of strategies through the digitalization of operation for improving resource efficiency, reduction of the environmental impacts of wastes and enhancing productivity.
Lean Industry 4.0	The application of lean thinking practices and methods to fully exploit Industry 4.0 digital technologies both at the manufacturing plant level and at the product/services/PSS delivered one, pushing the usage of data and information occurring along their lifecycle to obtain value-focused knowledge and to streamline/avoid waste.
Lean Industry 4.0	A strategy to reduce complexity in the industrial area, as well as contribute to increasing value and reducing all types of wastes.
Lean Industry 4.0	The fruitful integration/combination of lean principles and tools and I4.0/digital technologies
Lean Industry 4.0	The definition should integrate the principles of lean with the practices of industry 4.0. However, it is important to gather all objectives of industry 4.0 (including sustainability) and all principles of lean (including value and collaboration) in the definition of this term
Lean 4.0	Integration of Lean Thinking with tools of Industry 4.0 technology for enhanced productivity, improved quality and continuous improvement of customer value in the value chain.
Lean 4.0	An innovative socio-technical paradigm that leverages lean thinking to reduce complexity and 4.0 technologies to manage complexity
Lean 4.0	The role of Lean 4.0 is to build a solid basis of responsibility and accountability to preserve and protect the people-processes-technology triad without endangering the human spirit, human life, planet earth, and the ecosystem.
Lean 4.0	The combination of lean tools and digital technologies to develop new business models, create value for customers and leverage digital transformation in production systems.
Industry 4.0	Industry 4.0, revolution is characterized by the adoption of advanced technologies, that are integrating the physical, digital and biological worlds, impacting all disciplines, economies and industries, and providing customization with higher customer satisfaction.
Industry 4.0	The utilization of data in real-time to produce robust manufacturing systems. These can deliver outcomes and performance with great consistency despite the inherent sources of variability by automatically deciding on modifications required to compensate for deviations from the analysis of data taken in real-time. Data analysis methods can be expressed in terms of digital twins, the mathematical predictors of outcomes from inputs.
Digital Lean	LEAN for the digital age
Digital Lean Manufacturing	Digital Lean Manufacturing Systems build on data acquisition, data integration, data processing and data visualization capabilities to create different descriptive, predictive and prescriptive analytics applications to detect, fix, predict and prevent unstable process parameters and/or avoid quality issues inside defined tolerance ranges that may lead to any type of waste within the cyber- and physical- worlds.
Intelligent Lean	Making the most of human intelligence and digitalization in support of sustaining the lean E2E transformation.
Lean Manufacturing	Enhancement of the fantastic Lean principles with the facilitation of industry 4.0 technologies and capabilities (data gathering, visualization and interaction with workers, digital guidance of operators, digital daily meeting, etc. and data analytics to support problem-solving and prediction ... always with humans in the center). Adding green (resources efficiency) is obvious and easy for Lean, and is a must in most industrial sectors. Lean & Green 4.0 is the approach for the twin transition of the 21st century.
Lean Construction 4.0	Ability and process of avoiding waste and thus save inputs resources (time, money, energy, material resources, and human resources).
OPEX4.0	The end-to-end integration of the supply chain for maximizing value for all stakeholders including suppliers, manufacturers, distributors and customers

In trying to synthesize these it has been helpful to include the following aspects drawn both from the respondents and also found in wider literature:

- The socio-technical nature of the subject (Trist and Bamforth 1951; Emery 1959; Kumar, Zindani, and Davim 2019),
- The use of both human and artificial intelligence (Elenkov and Manev 2005; Breque and De Nul 2021),
- The wide multi-level nature of *Lean* (Hines, Holweg, and Rich 2004; Pagliosa, Tortorella, and Ferreira 2021),
- The wide nature of the *Industry 4.0* technologies (Moeuf et al. 2017b; Shahin et al. 2020),
- The focus on both the organization and the wider supply chain (Sharma, Jamwal, and Agrawal 2020; Kyrillos et al. 2021),
- The simplicity reduction nature of lean and complexity management nature of *Industry 4.0* (Villalba-Díez et al. 2020; Fields and Sanders 2021),

- The required focus on sustainability and the circular economy (Ganjavi and Fazlollahtabar 2022; Javaid et al. 2022), and
- A focus on the needs of the employees (Gallo et al. 2021; Hines 2022).

As a result, the current authors, of diverse views, felt it was best to provide an all-inclusive definition that took into account the plurality of views on the subject. The detailed definition of *Lean Industry 4.0* from this research is:

An innovative socio-technical paradigm that uses both human and artificial intelligence and relies on the strategic, cultural, systems, and tools of Lean as well as the various Industry 4.0 digital technologies continually and discontinuously used to improve both single organisations and their supply chains with a focus on simplifying and managing complexity to benefit the triple bottom line and hence meet specific customer and organisational needs as well as the expectations of employees and wider society.

Table 10. Identified research gaps.

Key Research Gaps Grouped n = 142	No.	Key Research Gaps Sub-Grouped n = 142	No.		
Combining Lean and Industry 4.0	54	Paradigms, Models, Theories, & Frameworks	10		
		Lean and Industry 4.0: Chicken and Egg	9		
		Implementation Roadmap	9		
		Merging Lean People and Process with Industry 4.0 Technology	7		
		Contingent Factors	6		
		Results of Integration	5		
		Enablers and Inhibitors of Lean Industry 4.0	5		
		Multi-Site Organizations	1		
		Maturity Assessment	1		
		Aligning Goals	1		
		Human Issues	18	Human Impact and Involvement	12
				Human-Machine	6
		Practical Implication Cases	15	Practical Implication Cases	15
		Sustainability	9	Lean and Sustainability	5
Lean Industry 4.0 and Sustainability	4				
Competence/Training/Education	7	Training and Competence	6		
		Digitising Education	1		
Digital Twins	4	Digital Twins	4		
Inter-Disciplinary Research	3	Inter-Disciplinary Research	3		
Supply Chain	3	Supply Chain	3		
Widening Lean Industry 4.0	3	Widening Lean Industry 4.0	3		
Industry 4.0	3	Industry 4.0	3		
Analysis/Categorization of Digital Technologies	2	Analysis/Categorization of Digital Technologies	2		
Resilience	2	Resilience	2		
Real-time Process	2	Real-time Process	2		
Customer Focus	2	Customer Focus	2		
Research agenda	2	Research agenda	2		
Blockchain	2	Blockchain	2		
Lean	2	Lean	2		
Combining Computation and Digital	1	Combining Computation and Digital	1		
Intelligent Systems	1	Intelligent Systems	1		
Knowledge Sharing	1	Knowledge Sharing	1		
Data Analytics	1	Data Analytics	1		
Other approaches than Lean	1	Other approaches than Lean	1		
Legislation	1	Legislation	1		
Project Management	1	Project Management	1		
RFID and Connectivity	1	RFID and Connectivity	1		
Traceability	1	Traceability	1		

Lean Industry 4.0 – the future

This third section will review the results and discuss RQ5 around what the key researchers see as the gaps within the *Lean Industry 4.0* field that need to be addressed in future research and how might these be addressed. Some of the gaps can be considered about the future of *Lean* or the future of *Industry 4.0* although the most intriguing is about the future of *Lean Industry 4.0* as this combination offers synergistic opportunities not available in either *Lean* or *Industry 4.0* alone.

Many papers in the literature have identified one or a small number of gaps based on their research findings with more comprehensive viewpoints from Buer, Strandhagen, and Chan (2018), Ciano et al. (2021), Ejsmont et al. (2020), and Pagliosa, Tortorella, and Ferreira (2021). However, nowhere in the literature is there a framework for future research in *Lean Industry 4.0* as will be developed here. To allow for as much “voice-of-the-researcher” and avoid pre-defining clusters, the survey provided an open question on future gaps.

This yielded 142 specific answers from the respondents. There was a wide range of ideas as seen in Table 10. However, five main areas stood out: combining *Lean* and *Industry 4.0* (54), human issues (18), practical implementation cases (15), sustainability (9) and training/competence/education (7). These and other areas will be discussed within the context of our *Framework for Future Lean Industry 4.0 Research* (see Figure 3) which is in itself an area called for by two researchers.

The *Framework* is an attempt to provide the canvas for future research within *Lean Industry 4.0*. It is based on the gaps identified in this research together with inspiration from existing models. Of particular importance was the supply chain perspective from Ciano et al. 2021; the multi-level nature of strategic and operational lean levels (Hines, Holweg, and Rich 2004; Hines and Butterworth 2019); the obsolete, mature, and emerging technology classification of Núñez-Merino et al. (2020) and the addition of human factors (Romero, Stahre, and Taisch 2019a). Hence, the new *Framework* looks at the extended supply chain (horizontal) as well as strategic, system, and

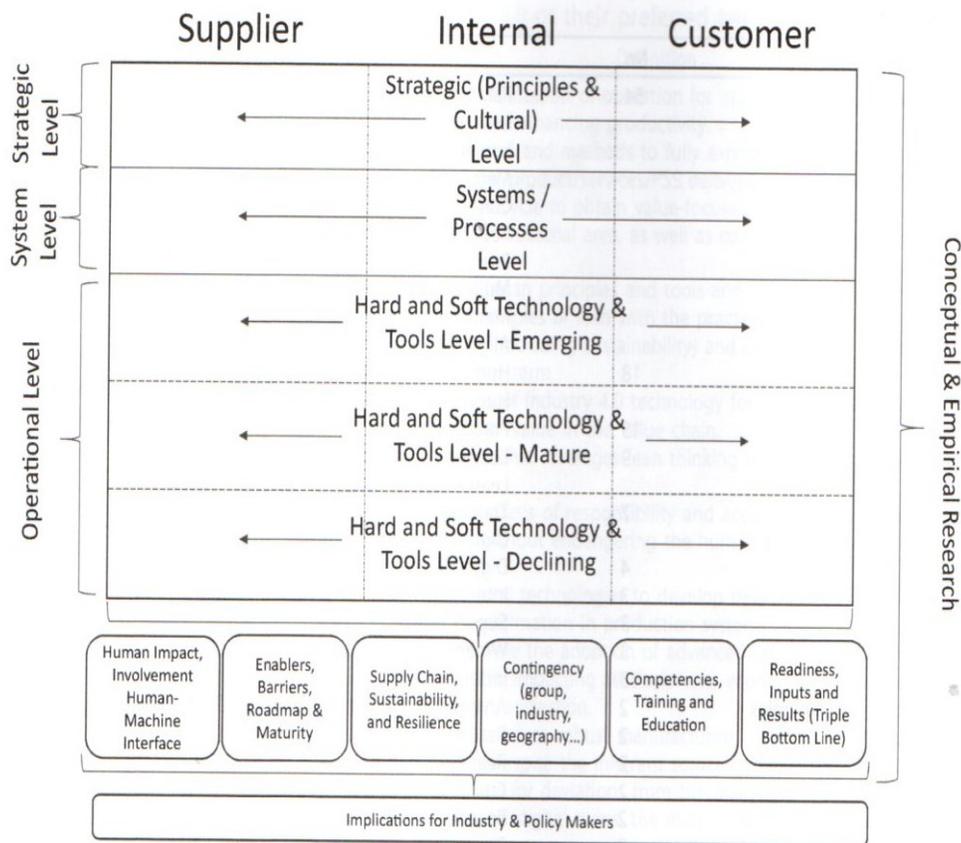


Figure 3. A Framework for Future Lean Industry 4.0 Research.

operational levels (vertical) with emerging, mature, and declining hard and soft technology and tools. The *Framework* also pinpoints the need for both conceptual and empirical work as well as gaps in six specific areas and resulting policy implications along the bottom of Figure 3.

Conceptual research

Turning to the conceptual level first, there was a widespread call (10) for paradigms, models, theories or frameworks to integrate *Lean* and *Industry 4.0*. It was suggested that these should be systematic and holistic, whilst also able to manage the evolutionary nature of integration as well as the subject itself. Other respondents suggested that these models should be practical and allow for contingency and be applicable also to project management industries such as construction. There was also a suggestion that they should be able to show how different functions are involved.

There is some recent early work in this area including high-level models such as the combination of technology capability, strategic flexibility, and *Industry 4.0* implementation (Sony, Antony, and Mc Dermott 2022) and the disconnected bridge model showing the existing lack of integration of *Industry 4.0*, Continuous Improvement and Respect for People (Hines and Netland 2022).

There are three more detailed models: the digital lean transformation framework by Romero et al.

(2019b) which focuses attention on (digital) strategic management, process (re-)engineering management, (digital) technology management, change (people) management, and (digital) risk management; the bi-directional support for *Lean* and *Industry 4.0* provided by Ejsmont et al. (2020), and the one-to-one relationship model which takes a broader supply chain context by Ciano et al. (2021). It would appear that there is a widespread desire for future work in this area.

Also mostly at the conceptual level, is a call for research merging the *Lean* people and process perspectives with the technology perspective of *Industry 4.0* (7) as well as the widening of the subject to include aspects such as maintenance and perspectives from Quality, Six Sigma and Agile (3). There was a viewpoint that *Lean* was strong at the strategic and system/process level as well as in its specific tools and human aspects. *Industry 4.0* was seen as strong in technology. The gaps mentioned were: how the more human approach from *Lean* could be combined with the more technological focus of *Industry 4.0*; how the subject could be addressed at multiple levels; and how could the *Industry 4.0* technologies more be discussed in an end-to-end way (as within Value Stream Maps or in Process Mining) rather than as single technologies.

At present the interpretation of *Lean* in the *Lean Industry 4.0* literature has been very much focused on the *Lean* tools and how these might be integrated with *Industry 4.0* technologies (Pagliosa, Tortorella,

and Ferreira 2021) meaning that the major value of strategic, people and system/process area has largely been missed except for a few texts such as Romero et al. (2019b)' and Tortorella, Giglio, and van Dun (2019). Therefore, there is much work to be done in this area.

Additional extensions of the *Lean Industry 4.0* subject could be in strategic areas such as Hoshin Kanri (Netland, Powell, and Hines 2019; Romero et al. 2019b), system process areas outside of the order fulfillment process (Bittencourt, Alves, and Leão 2021; Tortorella et al. 2020; Salvadorinho and Teixeira 2020) such as product lifecycle management (Synnes and Welo 2016; Cattaneo et al. 2017; Buer et al. 2021), order creation (Hines et al. 2008), after-market management (Rudnick et al. 2020; Lan et al. 2021) and people lifecycle management (Liker and Hoseus 2008; Hines 2022).

Conceptual/empirical research

There was a widespread call for more research into the causal relationships between *Lean* and *Industry 4.0* (9), the so-called “chicken-and-egg” paradox. Due to historical reasons, *Lean* usually precedes *Industry 4.0* and the majority, if not all (Pagliosa, Tortorella, and Ferreira 2021), of researchers concur that this is the right approach (Buer, Strandhagen, and Chan 2018; Tortorella and Fettermann 2018). There are indeed three possibilities: (i) *Lean* before *Industry 4.0*, (ii) *Industry 4.0* before *Lean* or (iii) for them to be implemented together (Ejsmont et al. 2020). Gaps were identified in terms of whether there was the best way, whether the answer was contingent and how analytical and simulation methods might help in finding the answer. This topic is worthy of further investigation both through conceptual and particularly empirical study.

There was also a call for more inter-disciplinary research (3) which might be of a conceptual or empirical nature echoing Stojanović (2022). As noted above the majority of researchers have a STEM or technological background (Elafri, Rose, and Boudemagh 2022) meaning that it may not be easy for these people to undertake research into more social areas which are required to give a more holistic view of the *Lean Industry 4.0* field. In particular, it would be helpful to supplement existing research expertise with that from human resource management and psychology; as well as subjects such as geography, economics and political science which might review more macro-economic effects; from biology and medicine that might be

helpful in sustainability research and even metascience for a more holistic perspective.

There were also gaps identified in further research into specific tools and technologies, specifically: digital twins, blockchain, RFID/connectivity and the categorization of digital technologies.

Empirical research

There is a clear shortage of empirical evidence within the *Lean Industry 4.0* field hence leading to 15 calls for more practical research on the real issue of working with *Lean Industry 4.0*. There was a particular emphasis on the need for case study research as much of the existing literature is based on surveys (Tortorella and Fettermann 2018). This might include which combination of tools and technologies should be applied and in which order (Pagliosa, Tortorella, and Ferreira 2021), insights into the “chicken-and-egg” paradox or comparative cases. In particular, gaps were identified in quantitative research as well as longitudinal cases (Tortorella, Giglio, and van Dun 2019; Ciano et al. 2021).

Human impact, involvement, and human-machine interface

One of the most important extensions of research into *Lean Industry 4.0* is in the human area with 12 researchers seeing a need for more research into human impact and involvement, rather than seeing people as static recipients of tools and technologies as they have often been portrayed in *Industry 4.0* (Nahavandi 2019; Breque and De Nul 2021) and *Lean Industry 4.0* (Romero et al. 2019b; Bittencourt, Alves, and Leão 2021). There was seen to be a major gap (6 researchers) in linking humans and machines in terms of collaboration and use of human and machine intelligence both from a technological and sociological perspective (Atwell 2017; Ansari, Erol, and Sihn 2018; Romero et al. 2019c). This would therefore help to cement the role of machines as helping humans and being human-centred rather than replacing them (Breque and De Nul 2021; Lagorio, Cimini, and Gaiardelli 2021). This might also focus on those who might find a transition to *Industry 4.0* more difficult such as older or disabled workers (Ullrich, Teichmann, and Gronau 2022).

Further research was also called for in understanding the role of the employee (Romero, Stahre, and Taisch 2019a) and leader (Tortorella et al. 2018) as well as in releasing creativity and teamwork, behaviors and wider human factors perhaps linking with the

emerging HRM 4.0 movement (Kumar 2018; da Silva et al. 2022).

Enablers, barriers, roadmap, and maturity

Enablers and barriers to implementation are in an area where there were 5 calls for further research. Some enablers have already been identified in the literature such as industry decision-makers consuming time and resources in evaluating the relevance to their companies and advice from public advisors or consultants (Irisgroup 2013; Stentoft and Rajkumar 2020). However, this research is far from exhaustive and more detailed research would be of value.

The literature is more forthcoming on barriers. Primary among these are expensive and time-consuming implementations (Ghobakhloo and Fathi 2019), the need for specialist knowledge (Haddud and Khare 2020) and the fact that all people are impacted and might not have been consulted or involved (Salvadorinho and Teixeira 2020). However, what are the other barriers and how might they be overcome? Are some of the technologies or mindsets within *Industry 4.0* a barrier to *Lean* or are some of the mindsets within *Lean* a barrier to *Industry 4.0*? It is noticeable that many of the well-known *Lean* authors are absent from discussions on *Industry 4.0*. (Mason-Jones et al. 2019). Have some people in *Lean* got a closed mind to technology?

Many of the respondents identified the gap in an implementation roadmap (9) or linked to this a maturity assessment, an area that has been echoed in the literature (Kolla, Minufekr, and Plapper 2019; Sassanelli, Rossi, and Terzi 2020; Elafri, Rose, and Boudemagh 2022). There are many examples of *Lean* roadmaps (Castro, Putnik, and Shah 2012; Duarte and Cruz-Machado 2019) and a few examples of *Industry 4.0* roadmaps (Geissbauer, Schrauf, and Hentrich 2015; Matt, Rauch, and Riedl 2021). However, integrated *Lean Industry 4.0* roadmaps and maturity assessments are a major gap. Respondents identified gaps in there not being a roadmap and whether one (or more) could be developed with built-in contingencies (Netland 2016). There was also a gap in identifying where to start and how to go about the journey depending on whether organizations had *Lean*, *Industry 4.0* or neither in place.

Supply chain, sustainability, and resilience

Many of the respondents had a background in supply chain or sustainability and in many cases, these were joined together with past work for instance in the

circular economy or resilience. There were 11 calls for more research in this wider area.

A clear need to extend much of the existing *Lean Industry 4.0* research outside of single entities was identified which would build on the existing recent body of literature (Danese, Mocellin, and Romano 2021; Reyes, Mula, and Díaz-Madroñero 2021; Choudhary et al. 2022; Filho et al. 2022). Particular gaps were identified in terms of understanding and incorporating customer perspectives and collaboration between organizations.

The suggestion was that the literature on integrating *Lean* and *Green* was as yet immature and needed to build on existing research (Zokaei et al. 2013; Ivanaj et al. 2021; Caldarelli et al. 2022). A similar suggestion was made for *Industry 4.0* and *Green* with only a few recent works (Villalba-Díez et al. 2020; Saberi et al. 2019). The same lack of research in *Lean Industry 4.0* and Sustainability (both new products and circular (economy) products) was also noted despite a few early works in these areas (Kamble, Gunasekaran, and Dhone 2020; John, Sampayo, and Peças 2021). A similar point was also made by 2 respondents about the integration of *Lean Industry 4.0* and Resilience particularly related to the COVID- or post-COVID environment, an area that does indeed seem under-researched in the literature with only a few examples (Belhadi et al. 2021, Hines and Netland 2022). This area is important as *Lean* has been criticized in the past for not being very resilient (Pereira, Christopher, and Da Silva 2014) and countermeasures from *Industry 4.0* may provide a way forward as it can cope better with complexity and dislocation (Tortorella et al. 2022). Future research might investigate whether and how the adoption of a *Lean Industry 4.0* approach might overcome perceived resilience weaknesses in a *Lean* approach.

Contingency

There has long been a debate within the *Lean* literature around contingency with early texts often highly prescriptive (Womack and Jones 1996) whereas more recent work in *Lean* and *Industry 4.0* respectively often proposes a more contingent approach (Netland 2016; Szász et al. 2020). A wide range of more contingent research was suggested in 7 calls. These include work around the size of the firm, industry, location, organizational culture, single versus multi-site operations and applications beyond manufacturing. As noted above, some of these areas such as industry size (Agostini and Nosella 2019; Kolla, Minufekr, and Plapper 2019), developed/developing countries (Ciano

et al. 2021; Pagliosa, Tortorella, and Ferreira 2021) and industry type (Reinhardt, Oliveira, and Ring 2020; Yang et al. 2022) have attracted at least some focus. However, the areas of organizational culture, single versus multi-site operations and applications beyond manufacturing appear to have received scant attention. It would also be of value to focus research outside of the well-mined Europe and Asia regions (Kipper et al. 2020; Ejsmont et al. 2020).

Competencies, training, and education

The evolving field of *Lean Industry 4.0* requires both new competencies as well as new combinations of competencies (Ansari, Erol, and Sihn 2018). Seven of the respondents identified gaps in how they might be identified, what these are (Maisiri, van Dyk, and Coetzee 2021) and how competency centers may be developed to train them both on a shop floor (Romero et al. 2020) and office environment (Mefi and Asoba 2021). Such competencies would include both hard and soft skills (Buer, Strandhagen, and Chan 2018; Ciano et al. 2021). In addition, the gap in how digital technologies might be used within the education system was also identified, for instance, the use of virtual reality (Hines and Netland 2022).

Readiness, inputs, and results

At present, there is a gap in understanding how ready organizations are to undertake *Lean Industry 4.0* and what inputs are required. In addition, the results of undertaking *Lean Industry 4.0* implementations are not that clear, partly due to the lack of empirical research. There is a call from 5 researchers for the economic results of implementations, such as productivity, quality, and profitability (Cattaneo et al. 2017; Pamornmast, Sriyakul, and Jermstiparsert 2019) as well as the human, wider societal, and environmental triple bottom line impacts (Ganjavi and Fazlollahtabar 2022; Integrated Filho et al. 2022) to be researched.

Implications for industry and policy makers

The last area included here is the wider policy implications of research into *Lean Industry 4.0*. This was only identified by one respondent, but it is felt that it should be included here for completeness. There are clear implications for industry in what it can gain from *Lean Industry 4.0* and how to go about achieving it. There are also clear implications for policymakers such as security, ethical, and support services in promoting *Lean Industry 4.0*. At this point, the literature appears to have only considered *Lean* and *Industry*

4.0 policies independently (Breque and De Nul 2021; Larrea and Estensoro 2021).

Security issues might be considered at the micro-scale in areas such as smartphones and wearable devices (Jaroenkunathum 2021), at a wider level such as cloud data storage (Zhe et al. 2017) or at a sectoral or national level (Laing et al. 2021). *Ethical issues* can occur in the use of personal data (Heikkilä, Honka, and Kaasinen 2018) and due to the wider instability of our society (Kucera 2018). Governments also currently tend to separate *Lean* and *Industry 4.0* industry support. For example, the various *Lean* industry support programmes offered by Enterprise Ireland (Enterprise Ireland 2022a) are currently offered separately from those in their Digital Transition Fund (Enterprise Ireland 2022b).

There is a clear need to consider *Lean Industry 4.0* policy more holistically.

Conclusions, further research, and limitations

Research conclusions

This research set out to address five research questions. The first RQ was around the research background of researchers within the broad *Industry 4.0* field. The community was found to be widely spread geographically, although primarily in Europe and Asia. There was evidence of some migration from developing countries, where undergraduate degrees had been taken, to more developed nations for university roles. There was a preponderance of researchers with an engineering or wider STEM background.

The second RQ concerned the present profile of key researchers working in the *Lean Industry 4.0* field. There was again still a dominance of researchers within engineering departments although there was a major move of people to management or management/engineering departments.

The interests of the key researchers within the field (RQ3) varied considerably. Researchers were found to have a particular interest in *Industry 4.0* technologies, sustainability, *Industry 4.0*, supply chain and people. Around half of the respondents were found to have no specific industry of choice for their research, with automotive being the most popular for the other researchers.

The fourth RQ concerned the definition of the general field. Both terms *Lean Industry 4.0* and *Lean 4.0* had a sizable following with the respondents, although the largest number opted for *Lean Industry 4.0*. Our recommendation is therefore that the research community gains consensus on the use of this term. It

proved difficult to pinpoint a definition of the term, partly as there is no agreed definition of *Lean* or *Industry 4.0* and partly due to the difficulty of trying to synthesize 87 responses. However, a detailed definition has been suggested that might be considered wide-ranging and inclusive in its scope.

A major part of this paper was devoted to the gaps that key researchers see within *Lean Industry 4.0* and how these might be addressed. The most cited gaps were in terms of combining *Lean* and *Industry 4.0*, human issues, practical implementation cases, sustainability and competence/training/education. In most cases, these differ from gaps simply in either *Lean* or *Industry 4.0* as they involve the combination of the two approaches creating both synergistic opportunities as well as apparent paradoxes such as that between the simplicity of *Lean* and the complexity orientation of *Industry 4.0*. They also address areas where *Lean* has been stronger and *Industry 4.0* less so (such as human issues) and *vice versa* (e.g., disruptive change). A *Framework for Future Lean Industry 4.0 Research* has been presented (see Figure 3) which may be of value to future researchers.³ The future of *Lean Industry 4.0* looks very exciting for academics, industry and policymakers with the conjoined approach increasingly replacing either individual foci.

The one over-riding trend that can be identified from this view of the past, present and future of *Lean Industry 4.0* is many key researchers start their careers with an engineering or STEM undergraduate degree, move to a management or management/engineering department and identify wider socio-technical interests, especially in the human aspects, supply chain or sustainability that might be best addressed through inter-disciplinary research.

This movement, and the whole *Lean Industry 4.0* field in general, is not without problems. The first is that it might be hard to change technical mindsets to more social studies research, coupled with the reluctance of certain parts of the *Lean* community to engage in a more technological perspective. The second is that there is currently a poor understanding for many in the *Lean Industry 4.0* field of the strategic, system, and human aspects of *Lean* and the technological opportunities within *Industry 4.0*.

There are two main practical implications for industry. The first is that practitioners should not fall into the trap of a disconnected approach to *Lean Industry 4.0*, where *Lean* sits within the operations or supply chain functions whereas *Industry 4.0* sits within engineering or ICT. This will require either the inter-related management of *Lean* and *Industry 4.0* or,

better still, the subject managed within one unified team. Second, and linked to this, people coming from a *Lean* background should be encouraged to open their eyes and embrace the opportunities created by the various *Industry 4.0* technologies, with more technology-oriented employees looking to incorporate a wider perspective, particularly about the role of people and focusing on technologies that help people rather than replace them.

Further research and limitations

The topic of further research in *Lean Industry 4.0* has consumed a large part of this paper so the detailed findings will not be repeated here. However, two areas are worthy of note. The first is the opportunity for a follow-up global piece of research to this using a similar approach to find out the past, present and future needs of key industrialists within the *Lean Industry 4.0* field and whether the directions identified by key researchers here will meet these needs. The second, is a parallel piece of research looking at the past, present and future perspectives of policymakers at regional, national and super-national levels and again whether these will meet the current and future needs of industry.

This paper is not without its limitations, many of which have already been discussed. Three will be overviewed here. First, it has only been possible to access the detailed view of 87 academics when a larger sample would have been beneficial. However, the 29% survey response will have at least come close to saturation. Second, the survey method restricted the choice of future gaps to 3 per researcher which might have limited niche innovative ideas as might the fact that the research was conducted with more established researchers rather than PhD or early postdoc researchers. Third, although open responses were received from the key researchers the level of depth within these was not as detailed as might have been received by other research methods such as focus Delphi studies, focus groups or interviews.

All in all, there is much work to do and hopefully, this paper might be of value in the evolving field of *Lean Industry 4.0*.

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