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Systematic Mapping Study of Digitization and Analysis of Manufacturing Data

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***Abstract*—**The manufacturing industry is currently undergoing a digital transformation as part of the mega-trend Industry 4.0. As part of this phase of the industrial revolution, traditional manufacturing processes are being combined with digital technologies to achieve smarter and more efficient production. To successfully digitally transform a manufacturing facility, the processes must first be digitized. This is the conversion of information from an analogue format to a digital format. The objective of this study was to explore the research area of digitizing manufacturing data as part of the worldwide paradigm, Industry 4.0. The formal methodology of a systematic mapping study was utilized to capture a representative sample of the research area and assess its current state. Specific research questions were defined to assess the key benefits and limitations associated with the digitization of manufacturing data. Research papers were classified according to the type of research and type of contribution to the research area. Upon analyzing 54 papers identified in this area, it was noted that 23 of the papers originated in Germany. This is an unsurprising finding as Industry 4.0 is originally a German strategy with supporting strong policy instruments being utilized in Germany to support its implementation. It was also found that the Fraunhofer Institute for Mechatronic Systems Design, in collaboration with the University of Paderborn in Germany, was the most frequent contributing Institution of the research papers with three papers published. The literature suggested future research directions and highlighted one specific gap in the area. There exists an unresolved gap between the data science experts and the manufacturing process experts in the industry. The data analytics expertise is not useful unless the manufacturing process information is utilized. A legitimate understanding of the data is crucial to perform accurate analytics and gain true, valuable insights into the manufacturing process. There lies a gap between the manufacturing operations and the information technology/data analytics departments within enterprises, which was borne out by the results of many of the case studies reviewed as part of this work. To test the concept of this gap existing, the researcher initiated an industrial case study in which they embedded themselves between the subject matter expert of the manufacturing process and the data scientist. Of the papers resulting from the systematic mapping study, 12 of the papers contributed a framework, another 12 of the papers were based on a case study, and 11 of the papers focused on theory. However, there were only three papers that contributed a methodology. This provides further evidence for the need for an industry-focused methodology for digitizing and analyzing manufacturing data, which will be developed in future research.

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I. Introduction

THERE is a huge focus currently on the upgrade of industrial capability and smart manufacturing, Made in China 2025 (MIC) is an initiative that was launched in 2015 to modernize China's industrial capability through intelligent manufacturing (i.e. Smart Manufacturing) [1]. MIC 2025 is inspired by Germany's "Industry 4.0" which is an initiative that was launched in 2011 to drive digital manufacturing forward by increasing digitization and the interconnection of products [2]. The European Factories of the Future Research Association (EFFRA) is engaged with the European Commission in a partnership called "Factories of the Future" [3]. The basis of this is the Factories of the Future Roadmap which outlines the need for innovation in manufacturing and contains many pointers to the concept Industry 4.0 [3]. These policy documents all highlight the need to upgrade manufacturing to an Industry 4.0, which is not possible without the digitization of processes. Terms like smart manufacturing, manufacturing digitalization and factory of the future are commonly used synonyms for Industry 4.0 [4]. Industry 4.0 is the fourth stage of the industrial revolution which involves the interconnectedness of products and services, brought about by their digitization [5]. The concept of Industry 4.0 first came about in 2011 with the aim of characterizing highly digitized manufacturing processes with information flowing between machines in a controlled environment and minimized human intervention [1]. Industry 4.0 uses digitization along with technologies and concepts including big data, the internet of things, advanced analytics, cloud computing, machine learning, artificial intelligence, robotics, 3D printing and augmented reality [6]. Although there has been a lot of research focusing on Industry 4.0 and its associated technologies, industrial adoption is still limited with only 33% of industry operating at high levels of digitization and 18% able to apply advanced analytics [7]. Data lie at the center of Industry 4.0 as the technologies associated with Industry 4.0 can be arranged based on their functions in relation to data [8]. The third industrial revolution employed digitization and information communication technology. Industry 4.0 is a further step toward smart manufacturing that uses digitization for the complete connection and communication of machines in a manufacturing environment [9], [10]. Smart manufacturing is the ubiquitous application of networked information-based technologies throughout the manufacturing enterprise [11]. Industry 4.0, as a whole, encompasses the digital

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transformation of conventional manufacturing practices through the digitization of manufacturing processes and the use of digital technologies and is gathering attention from many policy makers, academics and industrial experts [1].

Digitization paves the way for Industry 4.0, the use of digital technologies for exploiting the creation of value is referred to as digitalization [12]. Digitization results in improving process cycle efficiency, process control, data management and work productivity [13]-[15]. Business sectors that have a high level of digitization display the greatest growth in productivity [16]. A lot of the productivity increase seen in organizations recently is due to digitization and big data analytics [17]. Big data analytics simply refers to the use of analytics on a large volume of data in order to extract useful information. It is important for manufacturing organizations to understand the potential value arising from the digitization of processes and the use of advanced analytics on the resulting data. Advanced analytics is not a technology itself but involves applying various advanced analytical techniques and tools to big data to find information relating to problems and predict outcomes of solutions to these problems [18]. The Singapore Economic Development Board (EDB) developed the Smart Industry Readiness Index (SIRI) to assist manufacturers in transforming their processes toward Industry 4.0 [19]. The index defines 3 essential building blocks; Technology, Process, and Organization At the next level are 8 pillars representing critical aspects that organizations must focus on. SIRI shown in Fig. 1 is used in this study to aid in answering the research questions.

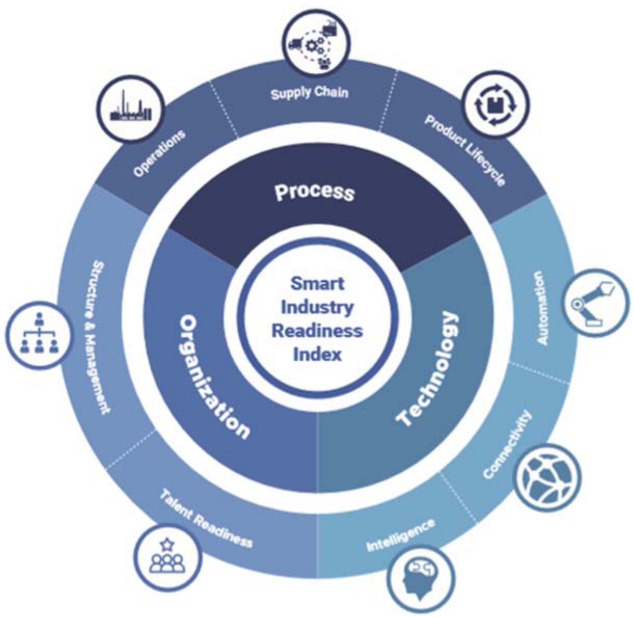

Fig. 1 SIRI building blocks and pillars [19]

II. Research Methodology

This study used a systematic mapping methodology to assess the current state of the research relating to digitization and analysis of manufacturing data. A systematic mapping study is a formal and well-structured research method that results in an investigation of great breadth with shallow depth [20]. This structured approach aids in the reduction of bias and ensures harmony of literature review efforts across the research team [21]. It seems that very few enterprises have reached a high level of digitization [22]. Therefore, the wide breath approach of a systematic mapping study is suitable for the area of digitization and analysis of manufacturing data as it is still a youthful research area that is need of standard methodologies to follow.

A. The Systematic Mapping Process

A systematic map, as described above, is a method used to structure a research area of interest. It gives an overview of the research area by determining the type of research that has been carried out, where the research has been published and the type of contributions and outcomes made [23]. Fig. 2 illustrates the systematic mapping process steps and outcomes, as the research progresses, the output from each step becomes the input for the next step [21]. The study began with the definition of the research questions, in line with the systematic mapping process. Search terms were identified and a primary search was conducted. Papers were retrieved from several digital databases and stored using a reference manager. A set of inclusion and exclusion criteria were used to manually screen each paper. The final set of papers that remained was analyzed by keywords to classify the type of contributions. Metadata relating to the final set of publications was stored in a digital repository. The publications data was then analyzed and visualized to answer the research questions set for this study.

B. Definition of Research Questions

The objective of this study was to gain an understanding of the digitization and analysis of manufacturing data and to capture a body of representative literature for this area. The first stage of the systematic process was to define specific research questions. Each of the research questions was defined to assess a different aspect of the topic to give a broad overview of the area being researched.

- RQ1: What is the publication fora relating to the digitization and analysis of manufacturing data?

The purpose of the first research question is to define the type of research undertaken in the area and the primary sources of the publications. Table III contains a defined set of types of research, used to classify the type of research of the publications. The intention of this research question is to investigate the number of publications each year in the area, the highest contributing institutions and authors along with the most commonly used keywords and the geographical distribution of the publications.

- RQ2: What are the benefits of the digitization and analysis of manufacturing data?

The purpose of the second research question is to find the most common benefits associated with the digitization and analysis of manufacturing data. By answering this research question, the study aims to outline the main advantages listed by the researchers in this area. The study aims to illustrate the

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distribution of benefits by the SIRI building blocks and pillars [19]. The intention of this is to help inform the areas of manufacturing that companies should find advantages in through the digitization and analysis of manufacturing data.

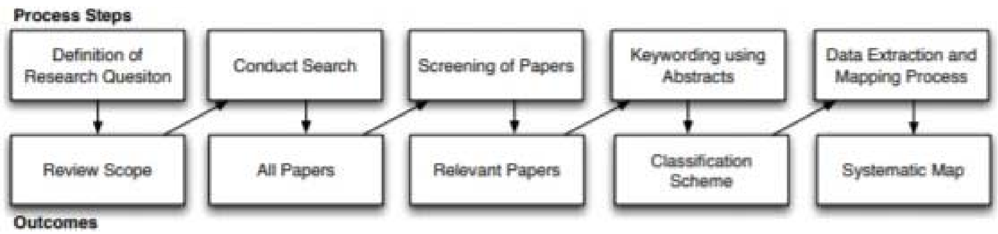

Fig. 2 Systematic mapping process[20]

- RQ3: What are the limitations of the digitization and analysis of manufacturing data?

The purpose of this research question is to investigate the most common issues or barriers slowing down the digitization of manufacturing data. The study aims to illustrate the distribution of limitations by the SIRI building blocks and pillars [19]. The intention of this is to help highlight the aspects of manufacturing that companies are facing challenges and need to focus efforts on.

- RQ4: What types of contributions are being made in the area of digitization and analysis of manufacturing data?

The purpose of this research question is to investigate the type of contributions of the papers in the area of digitization and analysis of manufacturing data. Table IV contains the definitions of the types of contributions. The intention of this research question is also to review the directions for future research suggested in the papers. By answering this research question, the study aims to highlight the type of research contributions that have previously been made and the types of contributions needed in future. Furthermore, the investigation into future research directions can provide an understanding and guidance for future work.

C. Creating the Repository

A reference management tool, Mendeley was used to store the publications used in this study. Microsoft Excel was used to document the screening phases of the systematic mapping. A digital repository storing all metadata relating to the publications was created in Microsoft Excel containing the title, institution, author, publication year, geographical location, type of research, type of contribution, benefits, limitations and future research for each publication.

D. Primary Search

The search terms deemed most relevant to this study based on the research questions were ‘digitization’, ‘manufacturing’, ‘data’ and ‘Industry 4.0’. Upon initial searches in the databases, it was noticed that irrelevant papers were returned due to a secondary meaning of the term ‘digitization’. In this study, the focus is on digitization meaning the process of converting analogue data into digital datasets [24]. Another use of the word digitization is in relation to dentistry in which CAD/CAM digitization is the scanning of gypsum casts or impressions [25]. Therefore, the search strings were altered so as not to return papers with the term ‘CAD’ or ‘CAM in the title, abstract or metadata. The publications in this study were sourced from five peer-reviewed databases; Scopus, Science Direct, Google Scholar, Web of Science and IEEE Xplore [24]. Each of the digital repositories had different search methods. The search was altered slightly to suit each of the databases and ensure that the results gave a comprehensive representation of the research area. Table I lists the search terms used in each of the databases.

TABLE I
SEARCH STRING FOR DATABASES

Database	Search
Scopus	((digitisation AND data AND (manufacturing OR "industry 4.0" OR factory OR "shop floor") AND NOT cad))
Science Direct	Digitisation AND (manufacturing OR factory) AND "industry 4.0" NOT CAD
IEEE Xplore	(((((("All Metadata":Digitisation) AND "All Metadata":Manufacturing) AND "All Metadata":Industry 4.0) NOT "Full Text & Metadata":CAD) NOT "Full Text & Metadata":CAM))
Google Scholar	allintitle: Digitisation AND Manufacturing OR Data OR "Industry 4.0"
Web of Science	(((digitisation AND data NOT CAD AND (manufacturing OR "industry 4.0" OR factory OR "shop floor"))))

E. Screening of Research

After completing the search in each of the digital repositories, a screening phase was required to eliminate non-qualifying papers; Fig. 3 illustrates the screening process used. The initial search in each of the databases yielded 592 papers as seen in Table II. Papers written in English and available in full-text were downloaded which resulted in 295 papers. Duplicates were removed using the function provided by the reference management software Mendeley; this resulted in 244 remaining publications. These papers were then screened using a chosen set of inclusion and exclusion criteria. There were 37 publications remaining after passing the papers through the three screening phases. Finally, a snowballing method was used to review the references of the remaining 37 publications and to include any papers deemed relevant to the study. The snowballing method resulted in a further 17 publications not previously included being added, yielding a final body of 54 papers used in the study.

F. Inclusion Criterion

For the research to be considered in this study it had to pass the defined inclusion criterion. The inclusion criterion required that the publications demonstrate a clear association

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with the digitization and analysis of manufacturing data. This requirement was met through the definition of the search strings used for each of the digital repositories. The papers were then filtered using a defined set of exclusion criteria to identify the most relevant research publications for this study.

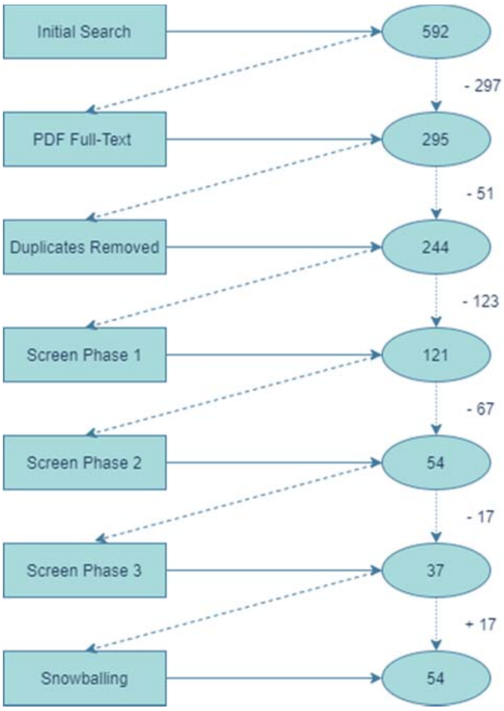

Fig. 3 Flowchart of screening process

TABLE II
SEARCH STRING FOR DATABASES

Digital Database	Number of Publications
Scopus	281
Science Direct	51
IEEE Xplore	4423
Google Scholar	69
Web of Science	592

G.Exclusion Criteria

Exclusion criteria were applied to the papers which passed the inclusion criteria. The exclusion criteria consisted of a set of filters to highlight the most relevant publications to the area of digitization and analysis of manufacturing data. The exclusion criteria consisted of the following;

1) Screen Phase 1: Review the title and abstract of each paper to determine its relevance to the study, remove any publications of lesser relevance.
2) Screen Phase 2: Review the title, abstract and introduction section of the remaining papers and remove publications that do not focus on, or contribute to the area of digitization and analysis of manufacturing data.
3) Screen Phase 3: Review the title, abstract, introduction, discussion and conclusion sections of the remaining papers and remove papers considered not relevant to the study.

H.Classification of Research

The publications in the study were classified in two aspects to provide a clear view of the current state of the research in the area of digitization and analysis of manufacturing data. The classifications used were the type of research and the type of contribution. The classification of the papers also aided in answering the set research questions.

I. Type of Research

The papers were classified by type of research according to published evaluation criteria seen in Table III [26].

TABLE III
TYPES OF RESEARCH

Type of Research	Definition
Validation	Research that investigates novel techniques that have not yet been implemented in practice.
Evaluation	Research that investigates techniques already in practice to understand the problems and uses of these techniques.
Solution	Research that proposes a new technique with its intended use and is illustrated with an example.
Philosophical	Research that describes a new conceptual framework.
Opinion	Research that contains the author's opinions about a particular technique.
Experience	Research that describes the personal experiences of the author with regard to one or more projects.

J. Type of Contribution

A systematic process known as "Keywording" was used to develop a classification scheme for the type of contribution of the research publications [20]. Firstly, keywords that reflect the contribution of the paper were chosen from the abstracts, and if needed, the introduction and conclusion sections. The set of keywords from different papers were combined together to develop a high-level understanding of the nature and contribution of the research in the topic area [21]. Table IV lists the set of classifications used in this study to describe the type of contribution of the research papers.

TABLE IV
TYPES OF CONTRIBUTION

Type of Contribution	Description
Architecture	Research that provides a theoretical view of how various components in a solution will sit together and interact.
Framework	Research that describes the theory of the problem under investigation.
Theory	Research that develops high-level guidelines and roadmaps for a particular problem.
Methodology	Research that presents low-level approaches to solving a particular problem.
Model	Research that produces mathematical models for solving particular problems.
Platform	Research that provides a system with hardware and software components.
Process	Research that presents low-level processes to solving a particular problem.
Tool	Research that develops an instrument that addresses a problem.

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III. Results

A. RQ1: What Is the Publication Fora Relating to the Digitization and Analysis of Manufacturing Data?

Fig. 4 illustrates the number of publications relating to the digitization and analysis of manufacturing data from 2007 to 2019. There were few publications in this area initially with one publication in 2007, 2008, 2009, and 2012. There were no publications for the next two years; however, there was an increase to four publications in 2015 and a spike of 10 publications in 2016. The lack of publications around digitization and hence, slow productivity growth before 2015 has been called the "productivity puzzle" in a report titled 'Twenty-five years of digitization' by McKinsey [16]. The report outlines that traditional companies have been slow to apprehend the productivity potential associated with digitization. They highlight the importance of countries, sectors, and firms embracing digital technologies in order to compete and perform more effectively. Although there was a decrease in the number of publications in 2017, the number of publications increased to 12 in 2018 and further increased again in 2019 to 20.

Fig. 5 shows the geographical distribution of publications relating to digitization using a world map. The map clearly indicates that Germany had the highest output of publications in this research area. Fig. 6 displays the top ten countries in relation to the number of publications in the area of digitization and analysis of manufacturing data. With almost half (42.6%) of the publications coming from Germany, it is evident that they are the leading country in this area. The next most contributing country is the United States of America with four publications, followed closely by India who contributed three papers out of a total 54 papers.

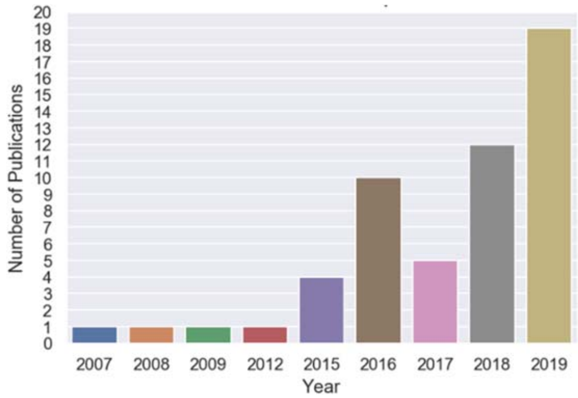

Fig. 4 Total number of publications per year

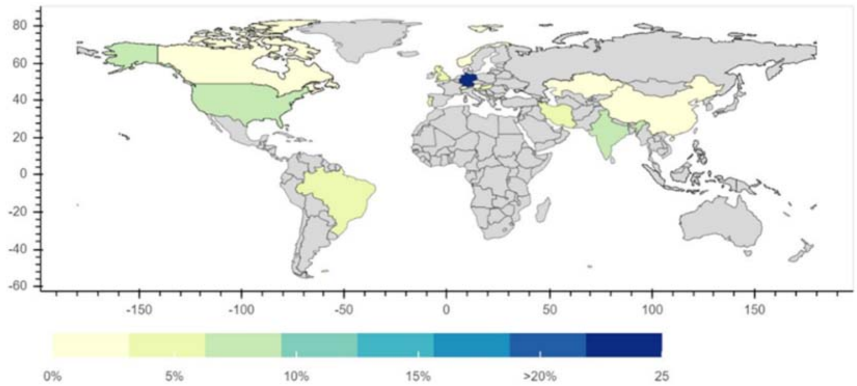

Fig. 5 Geographic distribution of publications

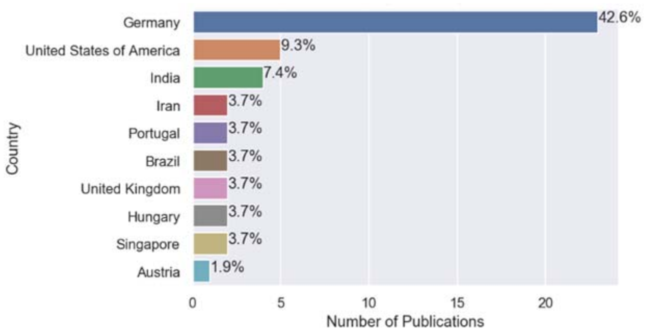

Fig. 6 Number of publications per country

Fig. 7 lists the top ten institutions in relation to the number of publications in the area of digitization and analytics for manufacturing. Fraunhofer Institute for Mechatronic Systems Design, a research institute located in Paderborn Germany, is in the lead with three publications, constituting 5.6% of all publications. Next at 3.7%, the University of Hormozgan in Iran, Aalen University of Applied Sciences in Germany and TU Dortmund University in Germany all contributed two papers out of the total fifty-four papers. Three of the top four institutions are located in Germany; this aligns with the results in Figs. 4 and 5, which highlight Germany as constituting the highest percentage of all publications.

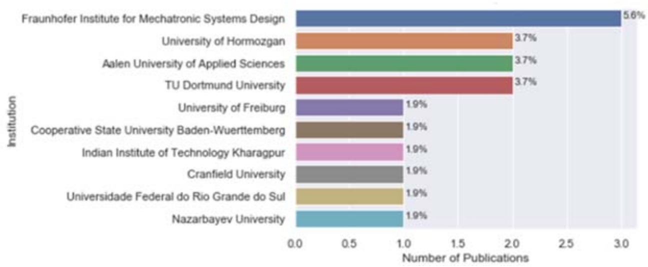

Fig. 7 Number of publications per institution

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Fig. 8 provides a breakdown of the top 15 keywords associated with the publications in the area of digitization and analytics for manufacturing. 23 of all publications (42.6%) listed 'Digitization' as a keyword. 'Industry 4.0' was the next most prominent keyword, listed in 40.7% of all publications. It seems logical for these words to both be prominent as in engineering and manufacturing there has been a shift to digitized production. The initiatives in this direction are known as 'industrie du futut' in France, 'industrial internet' in the United States of America and 'Industrie 4.0' in Germany [27]. It has also been stated in previous research that enterprises in Europe and in particular Germany have shown adequate progress in implementing Industry 4.0 related technologies in manufacturing processes [9].

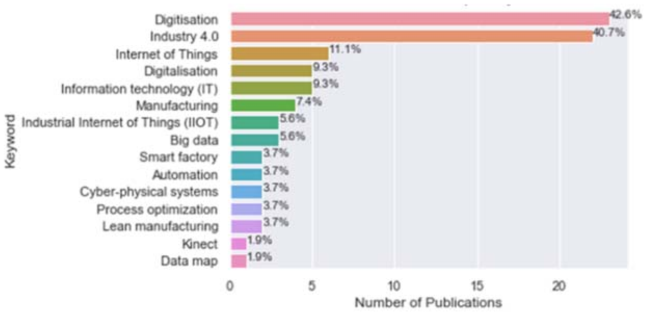

Fig. 8 Number of publications per keyword

Fig. 9 depicts the top ten authors contributing to the area of digitization and analytics for manufacturing. Robert Joppen is the most prominent author, constituting 5.6% of the publications. Eight other authors contributed two papers to the area.

Fig. 10 illustrates the breakdown of publications by journal, conference or book over the period 2007 to 2019. One publication was sourced from a book published in 2015. From the period 2007 to 2016, the split between journal and conference papers was approximately equal. In the more recent years, 2018 and 2019, the number of journal papers has been somewhat higher than conference papers; however, they both look to be on an increasing trend. This aligns with [28] expressing that academic investigation in the area of manufacturing digitization as part of the overall Industry 4.0 strategy is still in its infancy [29], [30] .

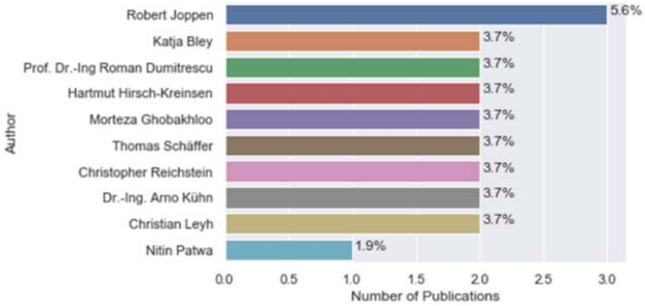

Fig. 9 Number of publications per author

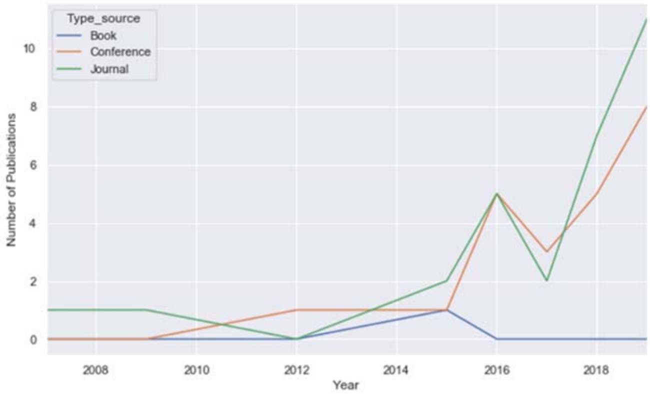

Fig. 10 Number of publications by source type

Fig. 11 presents the top ten journals in relation to the number of publications. The top three journals represent a third (33.4%) of all journal papers in the area of digitization and analysis of manufacturing data. The top research source, the Journal of Manufacturing Technology Management accounts for 16.7% of journal all papers in this area. "Computers in Industry" accounts for 10% of journal all papers and the International Journal of Advanced Manufacturing Technology accounts for 6.7% of all journal papers.

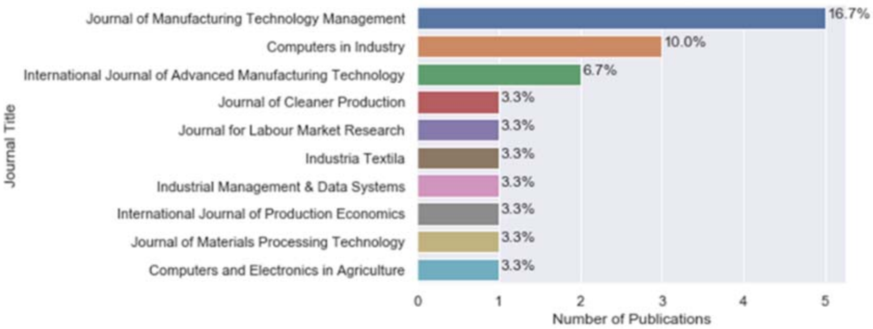

Fig. 11 Distribution of publications by journal

Fig. 12 portrays the top 10 conferences in relation to the number of publications in the area of digitization and analysis for manufacturing. The conference with the highest number of publications was the CIRP Conference on Intelligent Computation in Manufacturing Engineering 2018 with 8.7% of all conference papers in this area.

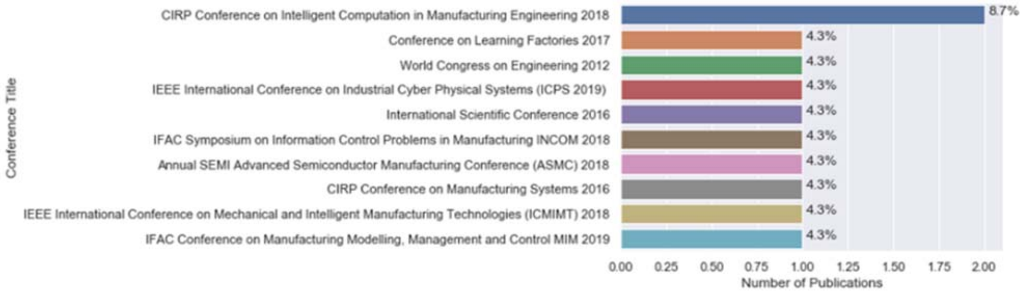

Fig. 1 Number of publications per conference

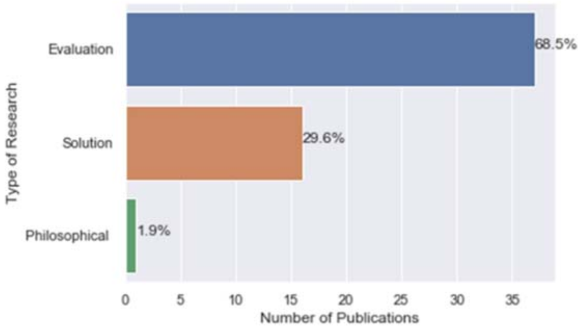

Fig. 2 Publications by type of research

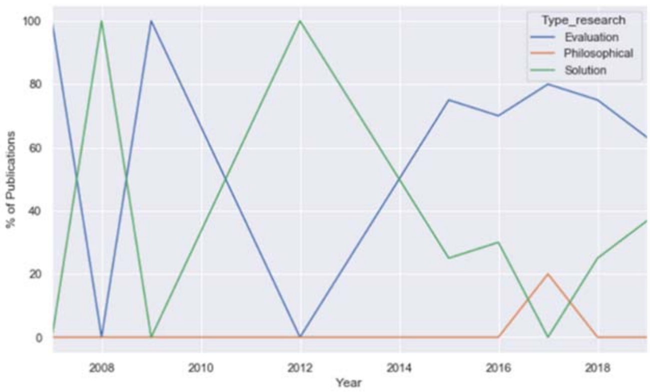

Fig. 14 Type of research 2007-2019

Fig. 13 provides a breakdown of publications by the type of research in the area of digitization and analytics for manufacturing. At 68.5%, evaluation is the most common type of research conducted. As described in Table III, evaluation research investigates techniques already in practice to understand the problems and uses of these techniques. Almost all of the remaining publications were solution type research. Solution type research proposes a new technique with its intended use, illustrated with an example. Evaluation type research, which accounted for over two thirds of all publications in this area, explores the problems, benefits and effects of a particular approach or solution. Fig. 14 illustrates the type of research publications by year. The split between types of research from the period 2007-2014 alters between 100% evaluation and 100% solution; this is due to the lower volume of publications in the initial years. From 2015-2017, the majority of the papers were evaluation type research. The percentage of solution type papers decreased during the same period, 2015-2017. However, in 2018 and 2019, the percentage of solution papers increased and the percentage of evaluation papers began to decrease.

B. RQ2: What Are the Benefits of the Digitization and Analysis of Manufacturing Data?

Fig. 15 gives a breakdown of the publications by the top ten most frequent benefits of the digitization and analysis of manufacturing data. Improving efficiency, outlined in 57.4% of the publications was the most prominent benefit found in the area of digitization and analysis of manufacturing data. At 48.1%, the second most common benefit outlined in almost half of the publications was the ability to have real-time data monitoring. Approximately one third of the publications outlined the benefits of reducing cost and reducing time. Other benefits of the digitization and analysis of manufacturing data found in over a quarter of the literature were the ability to create new business models, improve product quality and improve production planning and scheduling.

Fig. 16 illustrates a breakdown of the benefits of the digitization and analysis of manufacturing data by the SIRI pillars [19]. With 18.2% of all the benefits found in the literature, Operations and Supply Chain are the most common pillars. This is not surprising as the most common benefits in the papers as seen in Fig. 15, were increased efficiency, real-time data monitoring, reduced cost, and reduced time, which are all in relation to operations and supply chain. The next most common pillars at 13.6% are Talent, Structure & Management and Product Lifecycle. There are fewer benefits in the Connectivity, Intelligence and Automation pillars.

Fig. 17 illustrates a breakdown of the benefits of the digitization and analysis of manufacturing data by the SIRI building blocks. The Process building block is the most prominent with 50% of the benefits. As the benefits relate to manufacturing, it is not surprising that the most prominent building block is Process. Digitization of the manufacturing processes is one of the first stages in transitioning to Industry 4.0; therefore, it is understandable that more benefits lie in the process building block. The Organization building block contains 27.3% of the benefits outlined in the publications and

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the Technology building block contains 22.7% of the benefits.

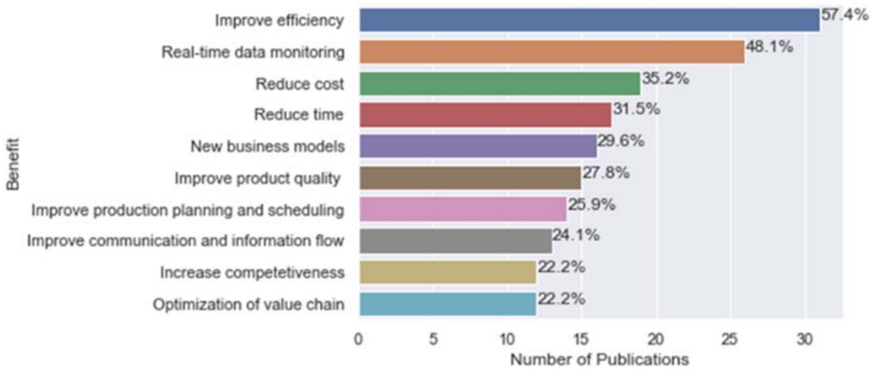

Fig. 15 Number of publications by benefit

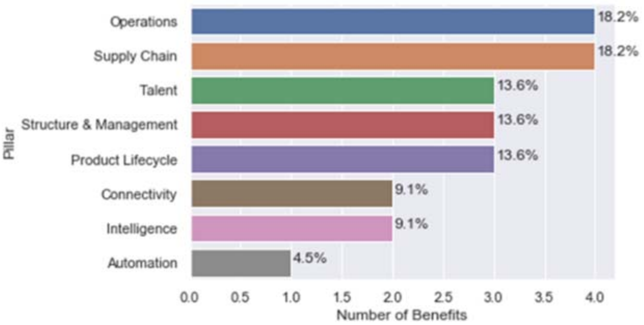

Fig. 16 Distribution of benefits by SIRI pillars

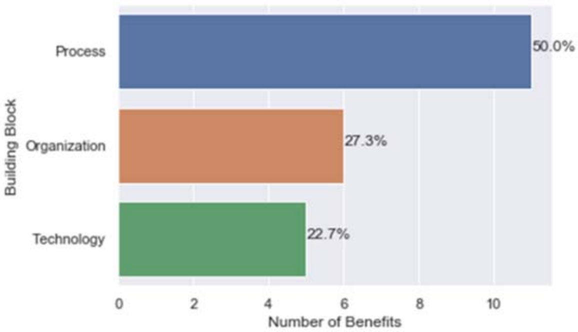

Fig. 17 Distribution of benefits by SIRI building blocks

C.RQ3: What Are the Limitations of the Digitization and Analysis of Manufacturing Data?

Fig. 18 illustrates the distribution of limitations associated with the digitization and analysis of manufacturing data. The most common limitation mentioned in 27.8% of publications in this area, is organization and process changes. The next most common limitations, in 25.9% of publications, were the need for enhanced skills and cybersecurity. Another common limitation found in 24.1% of the papers was data systems integration. Other limitations found in 20.4% of publications in this area were the quality of data and limited capabilities and resources. 18.5% of papers also stated the following limitations: hesitation to adopt, need for investment, information and communications technology (ICT) infrastructure and high implementation cost. Other limitations mentioned in 16.7% of all papers were complete organization acceptance and the novelty of the Industry 4.0 concept. There certainly exists a hesitation around the Industry 4.0 concept along with how an enterprise might migrate towards it. Although the digitization of manufacturing has gained a lot of attention in research recently, it is still unclear how to implement it in an interoperable manner using solid standards and technologies [31].

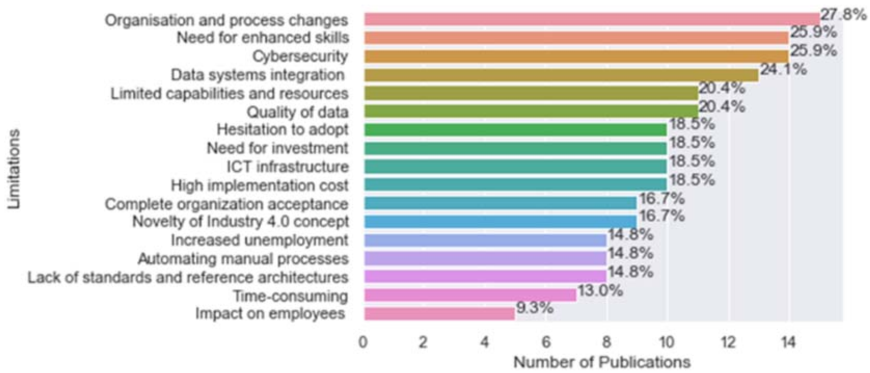

Fig. 18 Number of publications by limitation

Fig. 19 illustrates a breakdown of the limitations with the digitization and analysis of manufacturing data by the SIRI

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pillars [19]. With 42.9% of all the benefits found in the literature, Structure & Management is the most common pillar. The next most common pillar at 17.9% is Connectivity. Talent Readiness is also a quite common limitation in the area. There are fewer limitations in the Product Lifecycle, Automation and Intelligence pillars. There were no limitations in the Operations pillar.

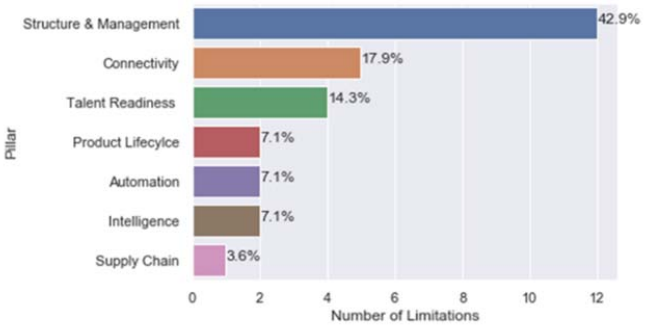

Fig. 19 Distribution of limitations by SIRI Pillars

Fig. 20 illustrates a breakdown of the limitations of the digitization and analysis of manufacturing data by the SIRI building blocks. With 57.1% of all the limitations found in the literature, the Organization building block is the most prominent. The Technology building block contains 32.1% of the limitations outlined in the publications and the Process building block contains 10.7% of the limitations. Organization was the most common building block for the limitations in this area, in comparison to Process, which was the most common pillar for the benefits in the area. It is important to understand that Industry 4.0 is a trend of digitization and automation and the associated technologies are progressing exponentially [32]. In order to overcome the limitations lying in the Organization pillar, manufacturers must focus on the make-up of the employees in their organization. Organizations should upskill their existing employees as well as look for new workers that are multi-skilled and flexible to adapt to any technology that may develop as part of Industry 4.0.

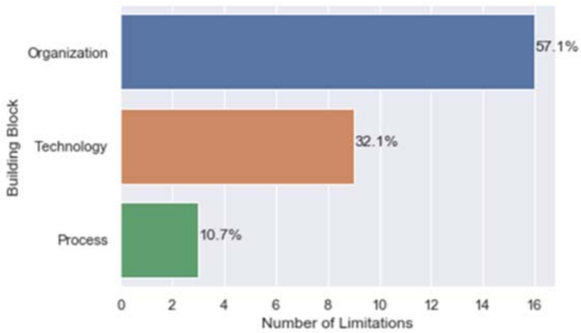

Fig. 20 Distribution of limitations by SIRI building blocks

D.RQ4: What Types of Contributions Are There in the Area of Digitization and Analysis of Manufacturing Data?

Fig. 21 illustrates the publications by the type of research contribution for digitization and analysis of manufacturing data. The top three types of research outputs constitute 66.7% of all research publications in this area. The most prominent type of research output at 24.1% is case study. The second most prominent type of research contribution is framework, constituting 22.2% of all publications. The third most common type of research contribution is theory, constituting 20.4% of all publications. Fig. 22 shows a breakdown of the type of contributions of the publications by conference, journal or book. Journals contributed more architectures, frameworks and theory whereas, conferences contributed more case studies, methodologies and models. Platforms and tools were from conference alone. Theory was the only type of contribution that originated from a book.

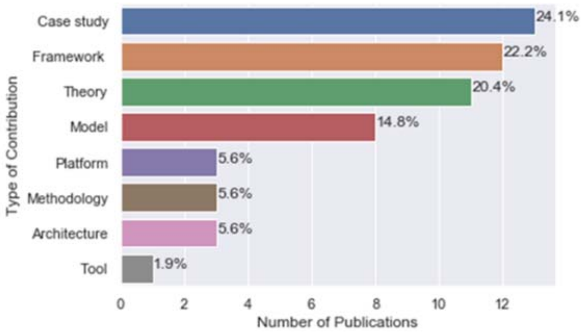

Fig. 21 Publications by type of contribution

Fig. 23 gives a breakdown of the type of research contributions per year for the digitization and analysis of manufacturing data. The contributions from 2007, 2008, 2009 and 2012 were solely models, case studies, theories and architectures respectively. The first framework was contributed in 2015 and then in 2016, 2018 and 2019 thereafter. There were theories contributed every year from 2015, although the percentage of theories contributed decreased each year. There were architectures contributed in 2012, 2017 and 2019. There were case studies in 2015, 2016, 2018 and 2019; case studies were the most prominent type of contribution in 2018 and 2019. The first methodology was contributed in 2016 and then in 2017 and 2019 thereafter. The first model published was in 2016 and there were models published each year after 2016. There were platform contributions in 2016, 2017 and 2019.

Fig. 24 gives a breakdown of the type of research by the type of research contribution. The results seen in Fig. 13 indicated that evaluation was the most common type of research, constituting 68.5% of all publications. Of the evaluation research papers, the most common types of research contribution were theories, frameworks and case studies. This aligns with the definition of evaluation type research as research that investigates the problems, benefits and effects of a particular approach or solution, this type of research related to the theory and case studies contributions. The second most common research type in this area was solution, constituting 29.6% of all publications. Of the solution research papers, the most common type of contribution was case study, followed by models, framework, methodologies and platforms. This aligns with the definition

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of solution type research as research that proposes a new technique with its intended use, often illustrated with an example. The philosophical type research papers contributed theories only.

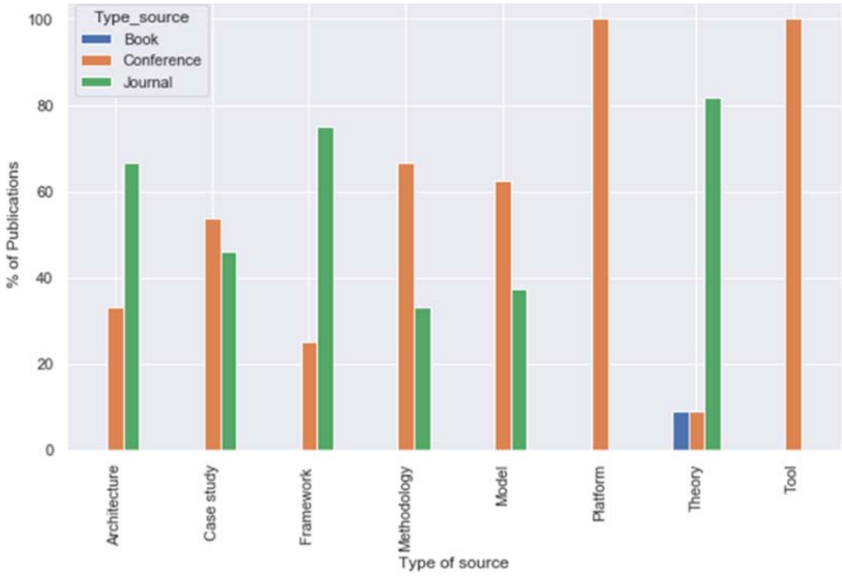

Fig. 22 Distribution of publications by contribution type and source type

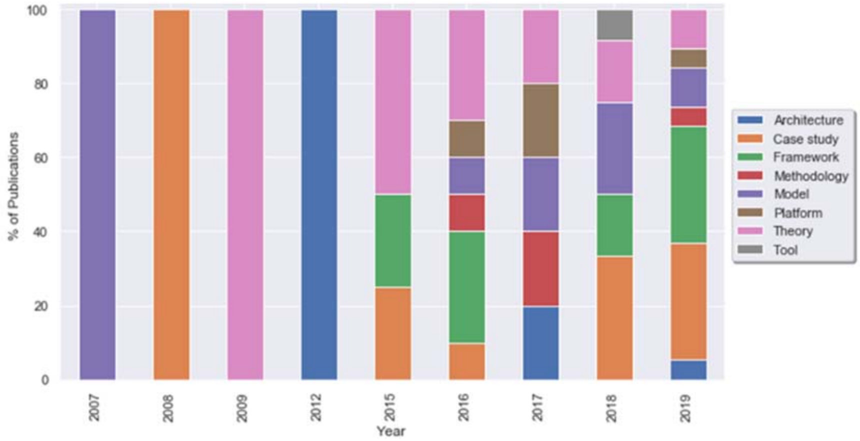

Fig. 23 Comparison of type of research contribution per year

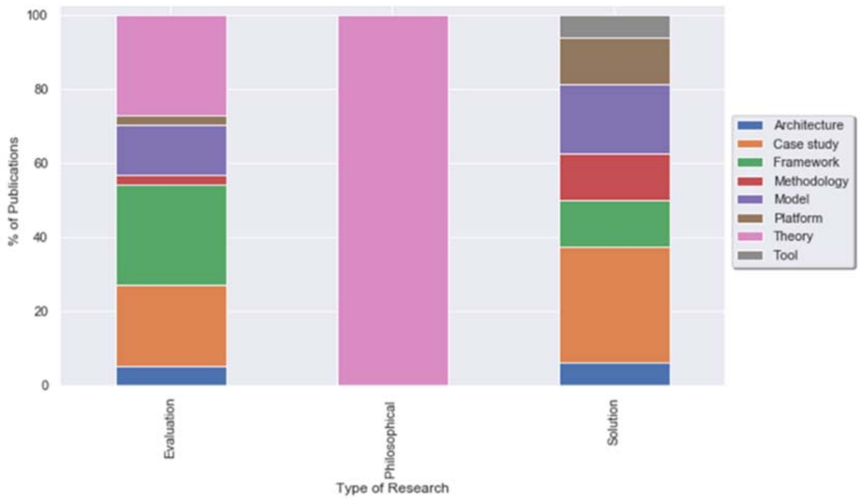

Fig. 24 Comparison of type of research by type of research contribution

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Fig. 25 displays the top 10 research directions suggested in the area of digitization and analysis of manufacturing data. The most prominent research directions highlighted in the literature at 14.3% was firstly, to validate a proposed model, method or framework. The second future research direction highlighted was to develop concepts or theories for a standard digitization approach. The next most common research directions suggested at 10.2% were to do a case study on lean manufacturing and cloud solutions and to explore the effects of Industry 4.0. The next most common research direction highlighted in 8.2% of all papers was qualitative studies such as interviews or studies.

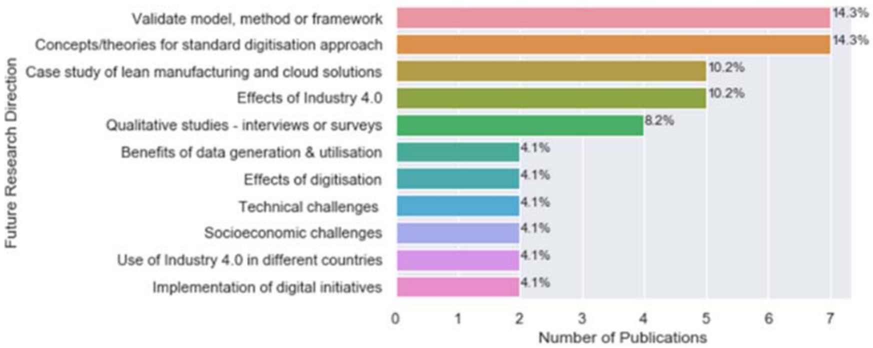

Fig. 25 Number of publications per research direction

IV. Discussion

A. RQ1: What Is the Publication Fora Relating to the Digitization and Analysis of Manufacturing Data?

There was initially little growth in the number of publications from 2007-2015. There was a 150% increase in the number of papers from 2014-2015. This suggests that the area of Industry 4.0 and digitization began to gain interest at this point. The number of publications in 2019 is double that of 2015. There was a 58.3% increase in the number of papers published between 2018 and 2019. Almost half of the research publications (42.6%) originated in Germany. Germany had the biggest contributing author, Robert Joppen, and institution, Fraunhofer Institute for Mechatronic Systems Design. Robert Joppen, the biggest contributing researcher in this area, has published multiple papers in relation to the digitization of manufacturing data. His research papers include but are not limited to; a process for the development of a digital strategy, developing and evaluating concepts for a digital platform, key performance indicators in the production of the future, data map – method for the specification of data flows within production, evaluation of investments in the digitalization of a production, and a practical framework for the optimization of production management processes [33]-[38]. The fact that Germany has the leading author and institute in this area can be explained by the fact that ‘Industry 4.0’ is a strategic initiative from the German government through the Ministry of Education and Research and the Ministry for Economic Affairs and Energy, aimed at pushing forward digital transformation [2]. This aligns with the most common keywords found in the literature being ‘Industry 4.0’ and ‘digitization’. The publications split between conference and journals are approximately equal each year, with slightly more journal publications in 2019. This would suggest that the research area is starting to mature slightly. The majority of papers from 2015-2017 being evaluation type research may be because Industry 4.0, along with its associated technologies, is a very broad concept and the research in this time focused on the effects, benefits and challenges associated with the implementation of Industry 4.0. An example is the paper by Oesterreich and Teuteberg in 2016 which focused on understanding the implications of digitization and automation in the context of Industry 4.0 [39]. Another example is the paper by Chen et al., in 2017 which looked at the key technologies, application case and challenges associated with the smart factory of Industry 4.0 [40]. Whereas, in more recent publications, in 2018 and 2019, there have been more solution type research papers including frameworks, strategies and roadmaps, with associated case studies. These types of publications have more detailed recommendations for how to transition to Industry 4.0. An example of this type of research is the strategic roadmap toward Industry 4.0 by Ghobakhloo in 2018 [31].

B. RQ2: What Are the Benefits of the Digitization and Analysis of Manufacturing Data?

Improving efficiency was the most common benefit of the digitization and analysis of manufacturing data. This aligns with an article by Schöder in 2017 which stated that large companies producing in high volumes can better achieve high efficiency gains from the digitization of manufacturing [41]. Most of the productivity increase seen in organizations nowadays originates either directly or indirectly from digitization and big data analytics [17]. There are fewer benefits in the Connectivity, Intelligence and Automation pillars, which are part of the Technology building block. This may be because the research in the area of digitization and analysis of manufacturing data outlines that digitization is the first step to undergo digital transformation. It is only when activities and processes become fully digitized and integrated, that advanced digital technologies can be implemented that would lie in the automation, connectivity and intelligence pillars.

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C. RQ3: What Are the Limitations of the Digitization and Analysis of Manufacturing Data?

The most common limitation found in the area of digitization and analysis of manufacturing data was organization and process changes (27.8%). This aligns with a paper by Eibl and Gaedke in 2017 which states that one of the most important challenges that companies currently face is the digitization of business processes and of the enterprise itself [42]. The second most common limitation found in the publications was the need for enhanced skills. Some aspects of Industry 4.0 require advanced expertise such as computer engineering skills [32]. There is a greater need for interdisciplinary training as well as lifelong learning and personalized learning [43]. This need for advanced skills is causing a barrier to the digitization and analysis of manufacturing data. In a paper by Müller et al. in 2019, they state that the lack of take-up of Industry 4.0 may be due to the need to support industry in re-skilling their workforce to be capable of implementing and making the best use of digital manufacturing technologies [44]. The research by Ghobakhloo and Fathi in 2019 into corporate survival in Industry 4.0 also states the need to provide extensive training for employees to be digitally literate and build skills needed for digital transformation [28]. This need for enhanced skills data suggests that engineers, who have the knowledge of the process do not have the data science skills needed to perform advanced analytics on the manufacturing data. Cyber security appeared as a limitation in over a quarter of the papers in this area. A survey was conducted by Eibl and Gaedki in 2017 to find the potential value of digitization for business from German speaking experts [42]. The survey found that 54% of participants states that based on the possibility of collecting enormous amounts of individual and company related data, the exposure and security of these sensible data is an important aspect. One expert said, "The risk of data theft and manipulation increases significantly". They concluded that data sensitive to the organization must be protected from theft, noise or attack to avoid any unwanted shutdowns or other losses [42]. Another common issue associated with the digitization and analysis of manufacturing data found in the publications was data systems integration. Data migration and the integration of the new systems into the existing production structures and databases has associated costs and complexities [45]. It is an important issue to be considered as data integration and data mining are the basis for advanced analytics [18]. The connection of systems in a digitized production is complex to create [46]. The process of digitizing corporate activity is a complex, multidimensional process that involves governance, management, infrastructure, technologies and analytical capabilities [15]. Other issues found with the digitization and analysis of manufacturing data were limited capabilities and resources, and quality of data. It is crucial when looking at the digitization and analysis of manufacturing data to consider that the data generated by intelligent equipment is mostly unstructured [40]. Research by Castelo-Branco et al. in 2019 investigating Industry 4.0 readiness in manufacturing found that the data available on the digitization of production processes are still sparse, even if it is evolving rapidly and that the technological developments allowed by the digitization of production processes are not ready for widespread use yet. Another noteworthy limitation found in the area was the hesitation to adopt. One of the major barriers of the digital transition may be in the mind-set of those accustomed to existing patterns shifting to a new platform [47]. Manufacturers may avoid embarking on the journey to digitization for fear of not having every single technological block and design principle in place [32].

D. RQ4: What Types of Contributions Are There in the Area of Digitization and Analysis of Manufacturing Data?

Fig. 23 illustrates the percentage of theoretical contributions decreased gradually year-on-year from 2015-2019. Case studies were the most prominent type of contribution in the last two years. In 2019, case studies and frameworks were the most common type of contributions. Overall, Fig. 21 highlighted that the most common types of research contributions found in the area of digitization and analysis of manufacturing data were case studies. Case studies seem to be a practical and useful type of research when attempting to undergo a digital transition in manufacturing. This is because the theoretical case of how to migrate to Industry 4.0 is positively biased and close to ideal case, whereas real-world situations may differ hugely due to unforeseen reasons [9]. The second most common type of research contribution found was frameworks. When conducting a case study in a manufacturing environment attempting to transition to a digital business, it would be highly beneficial to have a solid framework to use as a guide. Fig. 25 highlighted that the most common research direction found in the publications was the validation of a model, method or framework. The need for a standardized approach for digitizing manufacturing was the second most common research direction found in the area. The majority of experts in academia believe that the Industry 4.0 term itself is unclear, and manufacturing firms are having difficulties understanding the concept, and identifying the steps necessary for transitioning toward Industry 4.0 [32]. Future research should focus on standardizing process digitization efforts in manufacturing [48]. The next most common future research direction recommended in this area was a case study based on lean manufacturing with cloud solutions. Academic investigation on lean-digitized manufacturing in Industry 4.0 context is in its very infancy [49]. Therefore, future research should carry out exploratory case studies on the digitization of manufacturing and the associated value creation.

V. Threats to Validity

The terms used in the search string were chosen based on the research questions to be answered and the relevance of the papers returned. It is possible that some papers were not included in this study because of the difference in spelling of search terms such as ‘digitisation’ or ‘digitization and ‘industrie 4.0’ or ‘industry 4.0’. There may have been papers excluded from this research because of researchers using different terms for the area such as 'digitalization' or 'digital transformation' rather than digitization. The search string also excluded papers containing the terms 'CAD' or 'CAM'; this may have led to the exclusion of relevant papers. The digital databases used in this study were Scopus, Science Direct, IEEE Xplore, Google Scholar and Web of Science. There is a possibility that some research papers were excluded from this study, as other digital databases such as Engineering Village were not used. However, the five digital databases used along with snowballing reduce the risk of relevant papers not being included in the study.

VI. Conclusion

The research presented in this paper gave a wide, systematic mapping of the literature on the digitization and analysis of manufacturing data. The results for the research questions gave a thorough understanding of the publication fora, the benefits and limitations associated with digitization and analysis of manufacturing data and future research directions. This detailed mapping study highlighted the need for a standard digitization process for manufacturing firms to follow on the path to Industry 4.0. This study also pointed out that case study research is essential as the theoretical case of Industry 4.0 is idealistic and lacks the inevitable issues that exist in manufacturing. Therefore, future work following this study should focus on the development of a standardized approach for the digitization and analysis of data in a lean manufacturing environment with implementation via a case study. The need for enhanced skills was found as a common limitation for the digitization and analysis of manufacturing data. This would suggest that currently the engineers working on particular manufacturing processes in an enterprise do not have the data science expertise needed to perform advanced analytics on the manufacturing data to gain valuable information and insights about the process. On the other hand, data scientists may lack the engineering expertise and knowledge in relation to the manufacturing process. To test the concept of this gap existing between engineering and data science, an industrial case study was initiated in which the researcher embedded themselves between the subject matter expert of the manufacturing process and the data scientist. This case study has confirmed the existence of this gap between the data analytics and visualization team with the process engineers by virtue of a dearth of process-specific knowledge feeding into the analytics development pipeline. The confirmation of this gap existing in industry highlighted the need for a universal methodology for the digitization and analysis of manufacturing data in industry. Future research will focus on the development of a methodology for the digitization and analysis of data that merges the analytics and modelling knowledge of data scientists with the engineer's knowledge of the process and Lean manufacturing.

Appendix

TABLE V
Research Papers

Title	Publication	Type of Contribution	Year
Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry [34]	Computers in Industry	Framework	2016
The Data-Driven Process Improvement Cycle: Using Digitalization for Continuous Improvement [45]	IFAC-PapersOnLine 2018	Tool	2018
Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges [35]	IEEE Access	Architecture	2017
Topological Data Analysis to Solve Big Data Problem in Reservoir Engineering: Application to Inverted 4D Seismic Data [46]	SPE Annual Technical Conference and Exhibition 2015	Case Study	2015
The potential value of digitization for Business - Insights from German-speaking experts [37]	2012 BIOSIG - Proceedings of the International Conference of Biometrics Special Interest Group	Model	2017
A Complex View of Industry 4.0 [42]	SAGE Open	Theory	2016
Data Mining-Driven Manufacturing Process Optimization [47]	World Congress on Engineering 2012	Architecture	2012
The future of manufacturing industry: a strategic roadmap toward Industry 4.0 [31]	Journal of Manufacturing Technology Management	Framework	2018
Advanced analytics: opportunities and challenges [17]	Industrial Management & Data Systems	Theory	2009
Real-Time Monitoring System to Lean Manufacturing [48]	Procedia Manufacturing 2018	Case Study	2018
Digitalization: Opportunity and Challenge for the Business and Information Systems Engineering Community [49]	Business and Information Systems Engineering	Theory	2017
The expected contribution of Industry 4.0 technologies for industrial performance	International Journal of Production Economics	Framework	2018
Digitization of German Enterprises in the Production Sector-Do they know how " digitized " they are? [50]	Americas Conference on Information Systems 2016	Model	2016
Six Sigma based approach to optimize radial forging operation variables [51]	Journal of Materials Processing Technology	Case Study	2008
Change through digitization—value creation in the age of industry 4.0 [38]	Management of Permanent Change	Theory	2015
Digitization as a Catalyst for Business Model Innovation A Three-Step Approach to Facilitating Economic Success [52]	Journal of Business Management	Framework	2016
Automation, digitization and digitalization and their implications for manufacturing processes [53]	International Scientific Conference 2016	Theory	2016
Digitization of Industrial Work: developments paths and prospects [40]	Journal for Labour Market Research	Theory	2016
Industrial revolution - Industry 4.0: Are German manufacturing SMEs the first victims of this revolution? [54]	Journal of Industrial Engineering and Management	Framework	2015
Digitization in wood supply – A review on how Industry 4.0 will change the forest value	Computers and Electronics in Agriculture	Architecture	2019

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Title	Publication	Type of Contribution	Year
chain [39]			
Digitisation and Indsutry 4.0 in the Portugese T&C sector [55]	Industria Textila	Framework	2019
Strategic IT management: how companies can benefit from an increasing IT influence [56]	Journal of Enterprise Information Management	Model	2018
The Application Center Industrie 4.0 - Industry-driven Manufacturing, Research and Development [57]	Procedia CIRP 2016	Platform	2016
Estimating digitization efforts of complex product realization processes [43]	International Journal of Advanced Manufacturing Technology	Model	2018
Reflections on societal and business model transformation arising from digitization and big data analytics: A research agenda [58]	Journal of Strategic Information Systems	Theory	2015
The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems [59]	Procedia Manufacturing 2017	platform	2017
Collecting data in the assessment of investments within production [41]	Procedia CIRP 2019	Model	2019
Manufacturing conversion cost reduction using quality control tools and digitization of real-time data [14]	Journal of Cleaner Production	Case Study	2019
Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union [60]	Computers in Industry	Theory	2019
The digitisation of food manufacturing to reduce waste – Case study of a ready meal factory [61]	Waste Management	Case Study	2019
Antecedents and consequences of Internet use in procurement: An empirical investigation of U.S. manufacturing firms [62]	Information Systems Research	Model	2007
Digitisation of a moving assembly operation using multiple depth imaging sensors [63]	International Journal of Advanced Manufacturing Technology	Methodology	2016
Data map - Method for the specification of data flows within production [64]	Procedia CIRP 2019	Methodology	2019
Customer expectation from Industrial Internet of Things (IIOT) [65]	Journal of Manufacturing Technology Management	Framework	2019
Oil and Gas 4.0 era: A systematic review and outlook [21]	Computers in Industry	Theory	2019
The challenges of digitisation and data analysis in the maritime domain [66]	Maritime Affairs	Theory	2018
Industry 4.0: Redefining Manufacturing in Kazakhstan [9]	2019 International Conference on Advanced Communication Technology (ICACT)	Model	2019
An 'Industry 4.0' digital model fostering integrated product development [67]	2018 IEEE 9th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)	Model	2018
SIMMI 4.0-a maturity model for classifying the enterprise-wide it and software landscape focusing on Industry 4.0 [5]	2016 Federated Conference on Computer Science and Information Systems (FedCSIS)	Case Study	2016
The digitization of manufacturing and its societal challenges: A framework for the future of industrial labor [68]	2016 IEEE International Symposium on Ethics in Engineering, Science and Technology (ETHICS)	Framework	2016
Industry 4.0 readiness in Hungary: model, and the first results in connection to data application [69]	IFAC-PapersOnLine 2019	Framework	2019
Evaluation of investments in the digitalization of a production [33]	Procedia CIRP 2019	Case Study	2019
Reading Industrial Inspection Sheets by Inferring Visual Relations [70]	ACCV: Asian Conference on Computer Vision 2018	Framework	2019
Procurement 4.0: How the digital disruption supports cost-reduction in Procurement [71]	Production 2019	Framework	2019
Procurement 4.0: factors influencing the digitisation of procurement and supply chains [72]	Business Process Management Journal	Theory	2018
Opportunities, Challenges and Use Cases of Digitization within the Semiconductor Industry [12]	2018 29th Annual SEMI Advanced Semiconductor Manufacturing Conference (ASMC)	Case Study	2018
Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies [4]	Journal of Manufacturing Technology Management	Framework	2019
Enabling digitization by implementing Lean IT: lessons learned [73]	TQM Journal	Case Study	2018
Digitization of Work Instructions and Checklists for Improved Data Management and Work Productivity [13]	The 4th International Conference on Intelligent Transportation Engineering	Case Study	2019
Corporate survival in Industry 4.0 era: the enabling role of lean-digitized manufacturing [27]	Journal of Manufacturing Technology Management	Case Study	2019
Challenges of handling assembly information in global manufacturing companies [44]	Journal of Manufacturing Technology Management	Case Study	2019
Asset and Production Tracking through Value Chains for Indsutry 4.0 using the Arrowhead Framework [74]	2019 IEEE International Conference on Industrial Cyber Physical Systems (ICPS 2019)	Platform	2019
Adapting Warehouse Management Systems to the Requirements of the Evolving Era of Industry 4.0 [75]	ASME 2017 12th International Manufacturing Science and Engineering Conference (MSEC2017)	Methodology	2017
Smart Services Maturity Level in Germany [76]	2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)	Case Study	2018

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