Resiliency of Manufacturing Systems in the Industry 4.0 Era – A Bibliometric Analysis

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Abstract

Organizations experience mainly two kinds of disturbances: ones due to natural events (such as earthquakes, hurricanes, etc.) or ones resulting from man-made events (such as theft, power failure, etc.). Hence, many organizations strive to sustain resiliency to be able to deal with the various disturbances caused by different risks; and manufacturing systems are not any different. In manufacturing, disturbances could affect the outgoing product quality, the state of different machines, inventory levels, supply chains, or even entire factories. Manufacturing systems that are not resilient enough to withstand short- and long-term disturbances may suffer from dire consequences, such as delayed product launches, unfulfilled orders, customer dissatisfaction, etc. Due to the importance of having resilient manufacturing systems, the purpose of this work is to provide a bibliometric analysis of the recent research efforts on manufacturing systems resiliency in today's Industry 4.0 era. One of the findings of this work is that there is an increasing interest in this topic in the last five years.

Keywords
Industry 4.0, Manufacturing Systems, Resiliency

1. Introduction

The resilience of an organization is commonly defined as its ability to withstand both minor and major disturbances (Hosseini et al. 2016; Moghaddam and Deshmukh 2019; Ruiz-Martin et al. 2018; Srinivasan et al. 2016). Disturbances could be due to natural events (such as earthquakes, hurricanes, etc.) or due to man-made events (such as theft, power failure, etc.). These events are typically unpredictable, with low chances of occurrence but high impact, and could result in short- or long-term negative effects (Hosseini et al. 2019). Resilient organizations are expected to return to their original equilibrium state after any type of disturbance.

Being resilient should also imply that an organization is both *robust* and *agile* (Heinicke 2014; Hosseini et al. 2019; Moghaddam and Deshmukh 2019). Robustness relates to an organization's ability to absorb disturbances and to maintain its goal (Moghaddam and Deshmukh 2019; Ruiz-Martin et al. 2018; Srinivasan et al. 2016), whereas an organization's agility relates to its ability to recover from disturbances quickly (Heinicke 2014; Hosseini et al. 2019; Moghaddam and Deshmukh 2019). The concept of resilience should not be confused with *responsiveness*, as the latter refers to an organization's ability to react quickly and appropriately when the disturbances are too severe (Heinicke 2014; Srinivasan et al. 2016). Similarly, if an organization manages to survive disturbances and returns to a better position (i.e., uses the disturbances as an improvement opportunity), it is then called an *antifragile* organization (Ruiz-Martin et al. 2018).

Manufacturing systems are not any different; they also strive to sustain resiliency to be able to deal with various minor and major disturbances. In manufacturing, a disturbance is considered as any uncontrolled (or unexpected) type of change that affects its operational performance (Matson and McFarlane 1999). According to Srinivasan et al. (2016), these disturbances could be divided into: 1) *upstream*: disturbances from pre-manufacturing processes, such as issues with incoming material quality or supplier delivery; 2) *internal*: disturbances within the manufacturing environment, such as resource breakdowns or operator errors; and 3) *downstream*: disturbances which are due to issues beyond the manufacturing process, such as demand fluctuations.

Accordingly, almost all the components within manufacturing systems need to be resilient, as such disturbances could affect the outgoing products quality, the state of the different machines, inventory levels, distribution networks, or even entire factories. If manufacturing systems are not resilient enough to withstand the various types of disturbances, they may suffer from dire consequences including, but not limited to, delayed product launches, unfulfilled orders, or customer dissatisfaction.

The issue of manufacturing systems resiliency is even more significant in today's technological era, which allows more opportunities for disrupting the manufacturing environment. With the latest technological advancements and the emergence of the Industry 4.0[1] era, manufacturing systems[2] are constantly evolving and are becoming highly integrated cyber-physical systems that rely on both cyber and physical components. There is an increased reliance now on the digital thread; for instance, the usage of Computer-Aided Manufacturing (CAM) software is becoming almost indispensable within manufacturing systems. Furthermore, the growth of the Industrial Internet of Things (IIoT), which has also led to the Industry 4.0 initiative (Jeschke et al. 2017), has resulted in more emphasis on easier data exchange. Currently, more communication protocols and cloud computing tools exist, along with the increasing capability of various equipment to be easily connected to the internet.

Due to the importance of having resilient manufacturing systems in today's Industry 4.0 era, the purpose of this work is to provide a bibliometric analysis/review of the recent literature in this field. There has been, in fact, a number of literature reviews done within the context of manufacturing resiliency (A. Ali et al. 2017; I. Ali and Ismail 2019; Andrew et al. 2016; Bevilacqua et al. 2019; Hosseini et al. 2019; Kamalahmadi and Parast 2016; Karl et al. 2018; Singh et al. 2019; Tukamuhabwa et al. 2015); however, those reviews have mainly focused on the resiliency of supply chains. Furthermore, the impact of Industry 4.0 on resilience is often overlooked in the majority of the considered publications (I. Ali and Ismail 2019). Hence, a review on the resiliency of manufacturing systems with a much wider perspective and a focus on emerging concepts, such as IIoT and Industry 4.0, is needed.

The reminder of this paper is organized as follows; the next section contains details about the methodology of the review done. The findings of the performed review are presented in the section after that. Lastly, the paper is summarized in the final section, along with future work ideas.

2. Review Methodology

In order to achieve the objective of this work, a three-phase review methodology was followed. These phases are planning, implementation, and analysis. An overview of these phases can be seen in Figure 1, while their details are provided in the following sub-sections.

2.1 The Planning Phase

The planning phase involves four steps concerned with identifying the characteristics (parameters) of the search to be done. More specifically, in this phase the authors defined: 1) the aim of the review, 2) the initial selection criteria, 3) the used search statement, and 4) the platforms/databases used. Firstly, the aim of this review was defined as analyzing the manufacturing resilience literature from an Industry 4.0 perspective. Secondly, to better align with the scope of

[1] The initiative "Industry 4.0" refers to the fourth industrial revolution, which is based on concepts/technologies such as, but not limited to, the Internet of Things (IoT), Big Data analytics, Cyber-Physical Systems (CPS), Information Technology (IT), and cloud computing (Lu 2017; Morteza 2018; Muhuri et al. 2019; Oztemel and Gursev 2020; Vaidya et al. 2018; Zhong et al. 2017).
[2] Manufacturing systems within Industry 4.0 are typically referred to as "Smart" or "Cloud-based" manufacturing (Lu 2017; Vaidya et al. 2018), among others.

this work, the publications to be initially selected were limited to journal articles, conference proceedings, and books chapters published recently since the year 2015 and written in English only.

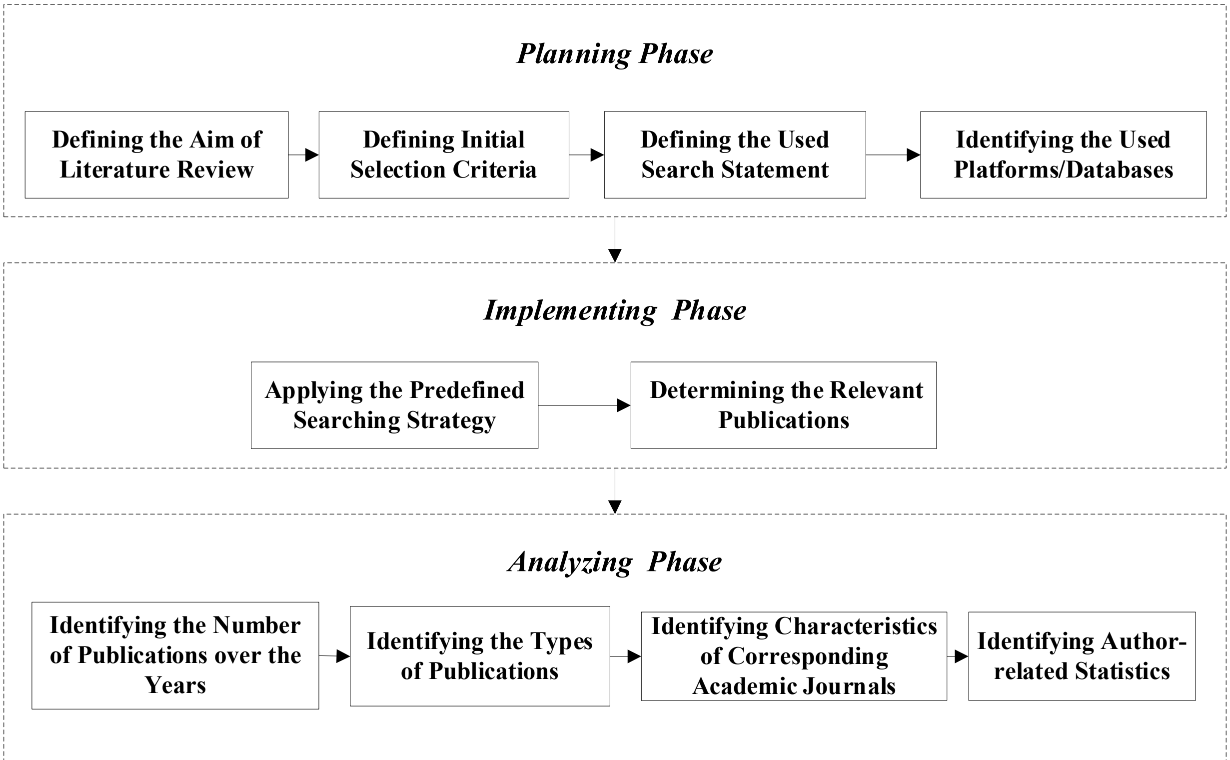

Figure 1. Review methodology overview (Adapted from Denyer and Tranfield (2009))

The purpose of the next two steps in this phase are to determine the most appropriate keywords to use and platforms/databases, for fulfilling the objective of this work. To this end, a list of preliminary key terms was first used to search for publications through both Google Scholar and Elsevier, to assess the prevalence of the research area under consideration and better understand its related terminology. The obtained publications helped the authors to then fine-tune the most promising keywords. Accordingly, the final search statement that would be used was:

(Resilience OR Resilient OR Resiliency) AND ("Industry 4.0" OR "Cyber Physical Manufacturing" OR "Cyber Physical Production System" OR "Smart Manufacturing" OR "Intelligent Manufacturing" OR "Cloud-based Manufacturing" OR "Smart factory" OR "Digital factory" OR "IIoT")

As for the databases/platforms to be used, it was decided to search the Compendex database through the Engineering Village platform, the Web of Science platform, and the Scopus database. The Compendex database contains a significant amount of peer reviewed and indexed publications across 190 engineering disciplines (Elsevier 2020a). The Web of Science platform consists of several literature search databases (Clarivate 2020), whereas Scopus is considered to be the largest abstract and citation database of peer-reviewed literature (Elsevier 2020b).

2.2 The Implementing Phase

As a first step in this phase, the search statement defined in the previous sub-section was used, in early November 2020, to search for terms only within the subject, title, abstract, or keywords[3] of the different publications, along with

[3] For the Engineering Village platform, the search was conducted within the subject, title, or abstract fields, whereas in the Web of Science platform and Scopus database the search was done within the title, abstract, or keyword fields.

ensuring that the initial selection criteria are included. A total of 470 publications were initially obtained as a result of applying the search strategy across the different platforms/databases.

The next step was then concerned with determining which of the resulting publications are relevant and aligns with the aim of this review. This determination involved the following steps/filters to eliminate the irrelevant papers:

1. Identifying the duplicate publications.
2. Screening the title and the keywords, to check the context in which they were used.
3. Reading the "Abstract" and "Conclusions" sections of each publication.
4. Skimming the important sections of each publication.

Accordingly, the number of publications was reduced significantly and a total of 39 publications were deemed relevant. It should be noted that there were nine publications that the authors could not obtain and were, thus, excluded from the total number of publications considered in the following phase.

2.3 The Analyzing Phase

The thirty-nine relevant publications were then analyzed, using bibliometric analysis. This analysis included publications characteristics, such as frequency of publications over the years and types of publications, along with the information about their corresponding academic journals and a few author-related statistics.

3. Findings

In this section, the results of the analysis conducted to evaluate the relevant publications identified in the review are presented. Firstly, the publications frequency over the considered years is shown in Figure 2. It can be clearly seen that there is an upwards trend over the years, indicating that the interest of researchers in this research area has been increasing.

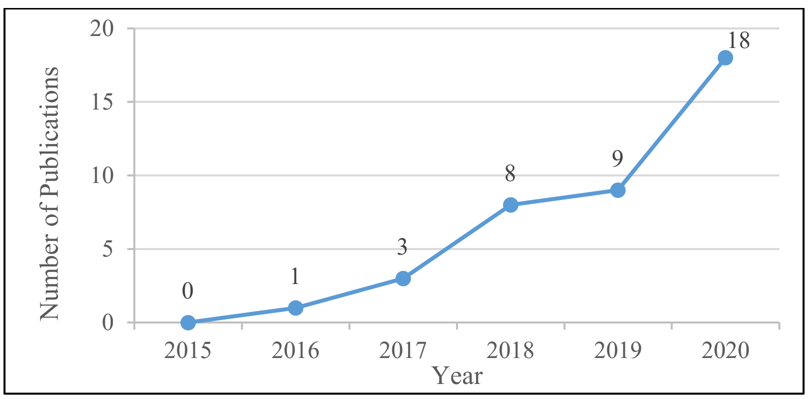

Figure 2. Distribution of the number of reviewed publications since 2015

Secondly, the breakdown of the types of the considered publications is shown in Figure 3. The most predominant type is journal articles (accounting for about 69% of the publications), followed by conference papers (almost 18%), and, lastly, book chapters (almost 13%).

Thirdly, Table 1 provides the ranking for the academic journals with the highest impact factors (larger than 2), where the largest impact factor is 9.936. Furthermore, a few of these journals included more than one publication. For instance, five journal articles were from the International Journal of Production Research and two articles were from the Annual Reviews in Control.

Finally, two author-related statistics are presented here, which are 1) the number of authors contributing to more than one publication and 2) the distribution of the different authors' country of affiliation. Regarding the former statistic, six authors contributed to more than one publication as shown in Figure 4. The author contributing with the largest number of publications is Ivanonv, D. Several of his publications were collaborated with Dolgui, A. and Sokolov, B. Also, Babiceanu, R. F. and Seker, R. have collaborated on two papers.

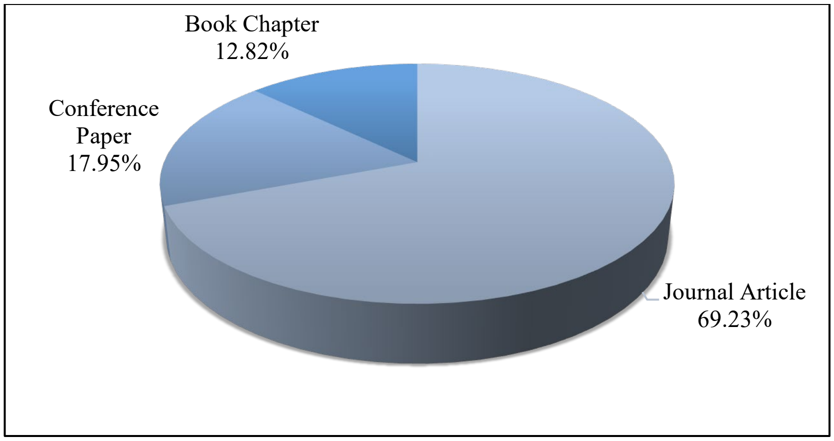

Figure 3. Types of publications considered

Table 1. Ranking of the highest impact factor (larger than 2) academic journals for the considered publications

Journal	2019 Impact Factor	Number of References
IEEE Internet of Things	9.936	1
Journal of Cleaner Production	7.246	1
International Journal of Production Economics	5.134	1
IEEE/CAA Journal of Automatica Sinica	5.129	1
Robotics and Computer-Integrated Manufacturing	5.057	1
Annual Reviews in Control	4.987	**2**
International Journal of Production Research	4.577	**5**
Computers & Chemical Engineering	4	1
Computers in Industry	3.954	1
IEEE Access	3.745	1
CIRP Annals	3.641	1
Production Planning & Control	3.605	1
Sensors	3.275	1
CIRP Journal of Manufacturing Science and Technology	2.991	1
Applied Sciences	2.474	1
International Journal of Logistics Research and Applications	2.152	1
Enterprise Information System	2.145	1

As for the authors' country of affiliation, a map with the geographic distribution of the considered publications is shown in Figure 5. More specifically, the highest three contributing countries are Germany, the United States, and France with 11, 10, and 9 publications, respectively, as listed in Table 2. Other countries that had multiple contributions included Russia, Spain, and the United Kingdom, among others.

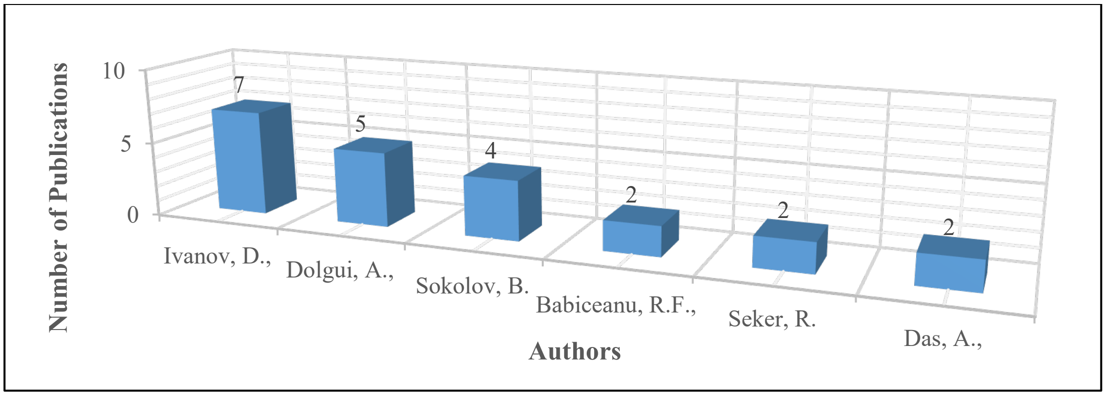

Figure 4. The number of publications for authors contributing with more than one

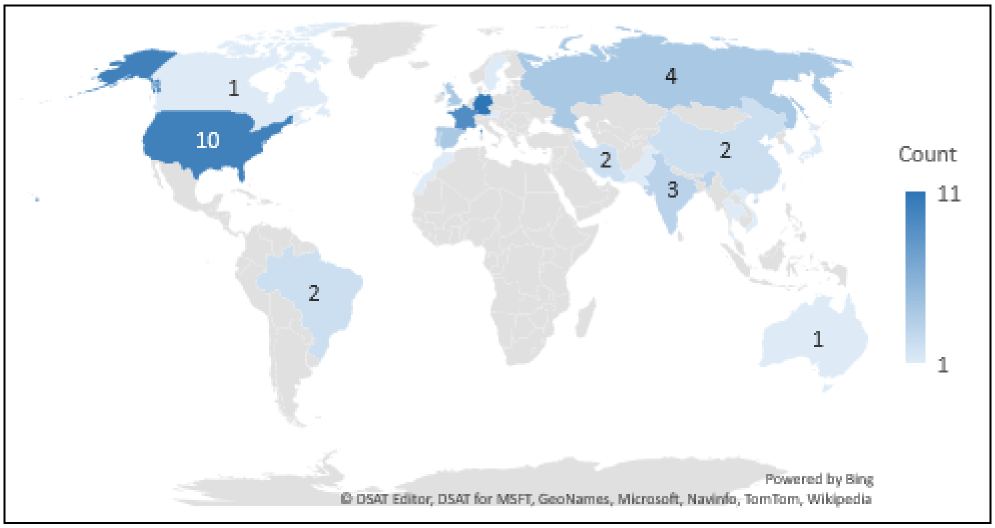

Figure 5. Authors' country of affiliation map

Table 2. Summary of authors' country of affiliation for countries having more than one associated publication

Authors' Country of Affiliation	Number of Publications
Germany	11
United States	10
France	9
Russia	4
Spain	4
United Kingdom	4
Portugal	3
India	3
Brazil	2
China	2
Iran	2

4. Conclusions

Manufacturing systems, like any other organization, experience both natural and man-made disturbances occurring unexpectedly and adversely affecting their operational performance. Accordingly, the resiliency of manufacturing systems against such disturbances has become an important topic in both academia and practice; especially in today's IoT and Industry 4.0 era. Hence, this work presented a bibliometric analysis through a three-phase review methodology on the recent publications in this field. From this analysis, it was observed that there is an increasing interest in this field during the last five years and the majority of the publications were from reputable academic journals. In addition, the top three countries with the most authors' affiliation are Germany, the United States, and France.

This work, despite its importance, is still in its preliminary stages and could be further developed in the future. One idea is to further extend the search space through backward and/or forward tracking of the considered publications. Another idea is to classify the reviewed publications according to their research area scope and research methodology used. This work has also the potential of allowing researchers to 1) identify the current state-of-the-art research areas within the field of manufacturing systems resiliency in the Industry 4.0 era and 2) highlight the existing research gaps for moving forward within this field.

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