Supply chain resilience and Industry 4.0 in the last decade (2013-2022): a keyword-based analysis

Federico Solari[a)], Natalya Lysova [a)], Eleonora Bottani [a)], Giovanni Romagnoli [a)], Andrea Volpi [a)] and Roberto Montanari [a)]

[(a)] *Dipartimento di Ingegneria e Architettura, University of Parma, Parco Area delle Scienze, 181/A 43124 – Parma – Italy (federico.solari@unipr.it)*

Abstract: The COVID-19 pandemic has significantly affected the supply chains worldwide, resulting in major disruptions with severe financial and operational impacts. Many organizations faced tremendous challenges, forcing them to change their perspective on supply chain management. In this scenario, the concept of resilience, intended as the capacity to rapidly recover from unexpected disruptions, has become increasingly important. To this end, the Industry 4.0 enabling technologies emerged as key tools for the optimization of planning, sourcing, and procurement strategies.

In this study, a keyword analysis was conducted to delineate the main themes surrounding the topic of supply chain disruptions in the last decade, as well as to determine the impact of the advent of Industry 4.0 in these themes. The keywords were classified according to their frequency and persistence of use. The analysis focused also on pre- and post-pandemic period, to evaluate the impact of COVID-19, and to detect the emergence of new (and relevant) themes. The results demonstrate that Industry 4.0 technologies are transforming supply chain management by generating new opportunities to improve the performance of logistics networks. The pandemic has accelerated this transformation, stimulating the development of new paradigms, principles, and models to optimize supply chain management and enhance resilience.

Keywords: Supply chain; resilience; disruption; Industry 4.0; keywords analysis.

I. INTRODUCTION

The fourth industrial revolution, or Industry 4.0, originated in 2011 in Germany, on a government initiative to promote the computerization of the manufacturing sector (Rojko, 2017). Specifically, the revolution involves the development of technologies that combine hardware and software tools and biological components (cyber-physical systems) to improve the efficiency and automation of processes by focusing on two main aspects: interconnection and communication. Kagermann et al. (2013) have detailed the three features that must be implemented to achieve the goal of Industry 4.0: horizontal integration between all activities and stakeholders, external to the company, who contribute to the product value; integration and communication between all levels of value chains to improve decision making; vertical integration between all levels of the organization starting from the data collected on-floor, up to the business management systems.

The first studies related to the application of Industry 4.0 in supply chain management appeared in 2014. However, it is since 2017 that there was a significant growth in the studies on this topic (Abdirad & Krishnan, 2020). The main benefits, that started emerging in the pre-pandemic period, were related to (*i*) the reduction in the product delivery time to customers; (*ii*) the reduction in the response time to an unexpected event; (*iii*) the significant increase in the quality of decision making (Barreto et al., 2017); (*iv*) the increased ability of the enterprises to manage complex and dynamic contexts and processes, and to integrate large-scale productions to increasingly specific customer needs (Rennung et al., 2016); (*v*) the improvement in the sales forecasting, production planning and logistics processes (Santos et al., 2017).

In recent years, a series of events that were difficult to predict, such as the COVID-19 pandemic, the political crisis between Russia and Ukraine, the climate change and drought warnings in many countries around the world, have highlighted that the supply chain is a fragile system in which the breakdown of one entity can cause the failure of the entire system (ripple effect) (Dolgui

& Ivanov, 2021). Indeed, during the recent pandemic, due to the restrictions applied by the governments, airports were closed, many manufacturers had to stop or strongly reduce their production operations, while many others had to exponentially increment their production rate (i.e., medical equipment suppliers). All this led to a chaotic situation in supply chains (Farooq et al., 2021). On the other hand, the war between the Russian Federation and Ukraine, affecting Europe since the last year, has caused significant changes in the relations between the nations, with profound impacts on both traditional commodity and raw material flows, as well as on energy supplies (Naz Farah & Kear Martin, 2023). In addition, the increasing attention that citizens, companies, and governments are paying to climate change is also profoundly affecting consumers' behaviour (Thøgersen, 2021).

In response to these phenomena, new trends have emerged globally, such as the progressive deglobalization, the development of new sourcing strategies, the rise of online shopping and home delivery services (Butt, 2022; Cui et al., 2023; Souiden et al., 2019), the increased digital awareness, and a greater need for digitization in various sectors, from services to logistics and manufacturing (Ye et al., 2022). It is therefore evident how supply chain management is still facing, significant disruptions, having to adapt to this new context and manage increasing complexities. In this context, Industry 4.0 technologies such as big data analytics, machine learning, predictive maintenance, blockchain, risk management, etc. are emerging as key tools for increasing resilience and managing supply-chain risks (Alvarenga et al., 2023; Bianco et al., 2023; Marinagi et al., 2023).

This study aims to assess, through a systematic keyword-based analysis, how the latest disruptions have changed the trends in the scientific literature. Scopus was selected as the reference database for collecting the relevant papers to be analysed for conducting the study. The resulting database of articles was appropriately analysed to assess, firstly, the distribution of scientific papers, and secondly, how the most frequently used keywords have changed over the years.

The remainder of the paper is organized as follows. Section 2 provides an overview of the adopted research methodology. Section 3 shows and discusses the key results obtained from the systematic keyword-based analysis. Section 4 describes the insights for future research that the present study suggests and provides concluding remarks.

II. Methodology

The first step of the analysis consisted in retrieving relevant articles in the literature about supply chain disruptions. To this end, a search was carried out using Scopus, one of the major bibliographic databases, that provides comprehensive coverage of scientific, technical, medical and social sciences literature. The query used to search for the articles consisted initially only of the keywords of interest:

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TITLE-ABS-KEY ( "supply chain" AND disruption )
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The search mechanism looked for these keywords in the title, abstract and keywords of the documents. After retrieving all the documents corresponding to the query requirements, the results had to be narrowed down, to keep only the ones relevant to the analysis.

The first filter applied to the documents was related to the year of publication, defined to consider the last ten years. First, the current 2023 year was excluded from the analysis because at the time of writing, the number of articles published is partial. The filter applied on the timespan, therefore, includes the decade 2013-2022:

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TITLE-ABS-KEY ( "supply chain" AND disruption )
AND PUBYEAR > 2012 AND PUBYEAR < 2023
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The articles were then filtered based on the type of document, considering only articles and conference papers. Also, documents written in English only were considered in this analysis:

```
TITLE-ABS-KEY ( "supply chain" AND disruption )
AND PUBYEAR > 2012 AND PUBYEAR < 2023
AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO
( DOCTYPE , "cp" ) ) AND ( LIMIT-TO (
LANGUAGE , "English" ) )
```

Finally, the documents were filtered based on the subject area. To this end, "Engineering", "Business, Management and Accounting", "Decision Sciences" and "Computer Science" were selected as significant categories. The final query, including all the filters applied, was:

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TITLE-ABS-KEY ( "supply chain" AND disruption )
AND PUBYEAR > 2012 AND PUBYEAR
< 2023 AND ( LIMIT-TO ( SUBJAREA , "ENGI" ) OR
LIMIT-TO ( SUBJAREA , "BUSI" ) OR LIMIT-TO (
SUBJAREA , "COMP" ) OR LIMIT-TO ( SUBJAREA
, "DECI" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR
LIMIT-TO ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO (
LANGUAGE , "English" ) )
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The procedure followed for identifying and selecting the papers is summarized in Figure 1.

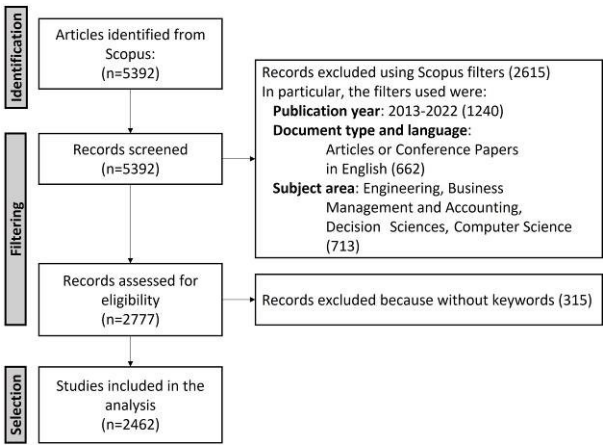

Figure 1. Procedure adopted for the research and the selection of the documents for the keyword-based analysis

The bibliographic data of the articles obtained was finally exported in CSV and RIS formats for further analysis. The RIS file was uploaded to VOSviewer™ bibliometric tool, to get an overall impression of the relevant author keywords and their respective timelines. Due to the high number of papers, the keyword analysis was limited to those that appeared at least 10 times. The identified keywords were then exported for further investigations.

The database in CSV format, as well as the relevant keywords identified with VOSviewer™, were imported to Microsoft Excel™ to perform a keyword-based analysis, according to the framework introduced by Fadlalla & Amani (2015). First, both the keywords used for the query, i.e., "supply chain" and "disruption", and the keywords where these terms appeared, e.g., "supply chain disruptions" and "supply chain management", were removed from the keyword list. This operation was carried out to minimize the influence of the keywords used in the query on the outcomes observed. Obviously, the articles without keywords were also removed from the database.

Each relevant keyword was then described in terms of its frequency of appearance and persistence of use in time, the latter defined as the number of years the term has been adopted by the authors. Average frequency count (AFC) and average persistence count (APC) were calculated, allowing to classify the keywords into four groups based on their use in the last decade:

- If both the frequency and the persistence indexes were below the mean values AFC and APC, respectively, the keyword was classified as *emerging*;
- Keywords with high frequency of use and low persistence were defined as *trendy*;
- Keywords with low frequency and high persistence values were classified as *intermittent*;
- Finally, keywords with frequency and persistence values above the average were defined as *core* concepts.

This classification allowed for the determination of the main themes surrounding the topic of supply chain disruptions and the approaches investigated for the minimization of the consequent risks and negative effects.

A second analysis was performed by dividing the decade analysed into two periods: a *pre-pandemic* period, including the years 2013-2019 before the outbreak of the COVID-19 pandemic, and the *post-pandemic* period, including the years from 2020 to 2022. The frequency of appearance of the keywords was evaluated for the two periods to determine the trend in the most investigated topics over time, as well as to detect the appearance of new relevant themes, e.g., as a consequence of the COVID-19 pandemics.

III. Results and Discussion

The database retrieved from Scopus originally included 5392 articles. Following the first filtering criteria applied in Scopus, 2777 remained. Figure 2 shows the trend in the number of articles published over the decade of reference (2013-2022).

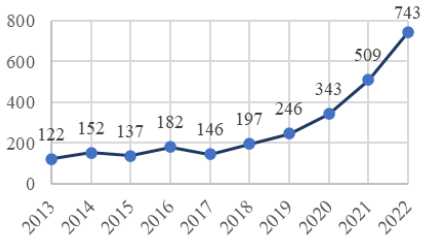

Figure 2. Number of articles published in the decade 2013-22

The figure shows a significant increase in articles concerning supply chain disruptions starting from 2018. This suggests that the pandemic was not the only event that made the researchers aware of the issue. Indeed, other events such as the real estate crisis in the U.S. in 2007 and the following economic crisis in 2008 resulting in the Great Recession, the Eurozone so-called "sovereign debt crisis" in 2010, the advent of Industry 4.0 in 2011,

the real-estate crisis in China in 2015, and the Brexit between 2016 and 2018, with their strong disruptive effects, highlighted the relevance of this issue and the need for investigations. With the advent of the pandemic in 2020, a further increase in published articles can be observed.

The analysis of the geographical provenance of the authors writing about supply chain disruptions in the last decade (Figure 3) shows that most of them were from the United States and China, which indeed were the countries most affected by the crises that occurred in the new millennium. The presence of India in the third position can be explained by the major tax reforms that were introduced between 2016 and 2017, the introduction of the Good Service Tax and the demonetization. In addition, there was also a rapid spread of the internet in India in recent years, which has led to significant growth in e-commerce and digitization, with strong consequences reflected in the supply chain.

With references to the sources of the documents, the International Journal of Production Research appears to be the journal with the highest number of publications about the supply chain disruptions, with 134 papers published in the decade 2013-2022 (approximately 4.8% of all documents analysed). International Journal of Production Economics classifies second, with 82 papers, while Computers and Industrial Engineering is the third source with 69 articles, covering 3.0% and 2.48% of the sample considered, respectively. Annals Of Operations Research, IFAC Papers online, Transportation Research Part E - Logistics and Transportation Review, International Journal Of Logistics Management, Sustainability, Supply Chain Management, Journal Of Cleaner Production, International Journal Of Operations and Production Management and Omega have published between 30 and 60 articles each on the supply chain disruptions in the decade considered.

Regarding the keywords, an initial overview of the sample was carried out using VOSviewer™, which was used to represent the keywords within a network, visualizing the links and correlations between them (Figure 8).

The keyword-based analysis was then conducted on Microsoft Excel™. The keywords that appeared at least 10 times in the papers (131) were extracted from the total list of terms (5928). These keywords were then filtered to exclude those used in the query, resulting in 94 keywords. The terms were classified based on their frequency and persistence indexes into four categories: *core* (15), *trendy* (6), *intermittent* (32) and *emerging* (41) (Figure 4). The keywords with high frequency, i.e., above the AFC value, are presented in Figure 5.

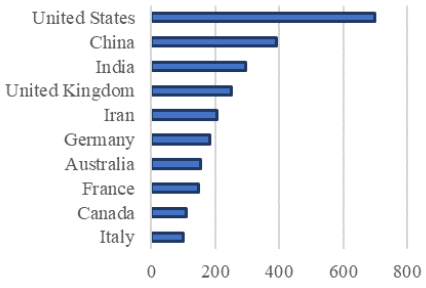

Figure 3. Top affiliation countries

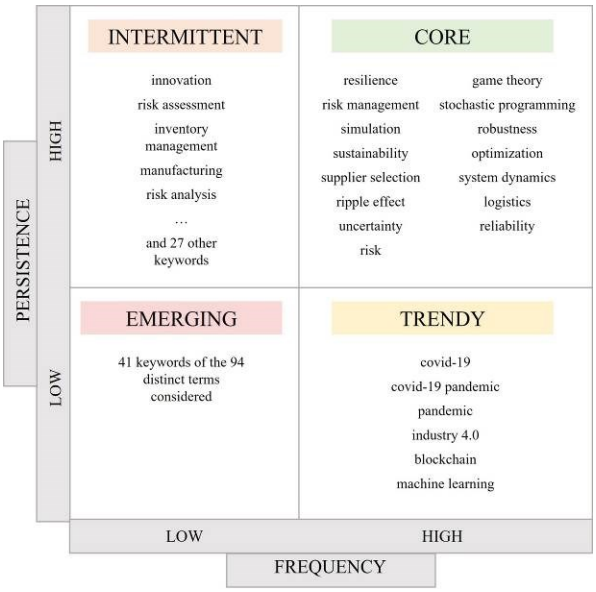

Figure 4. Classification of the selected keywords based on their frequency and persistence of usage

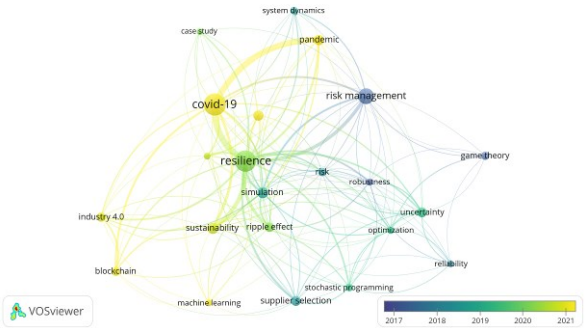

Figure 5. Network view of the keywords with high frequency, colored according to the average year of publication

Finally, a second keyword analysis was performed dividing the decade evaluated into two periods: the "pre-pandemic" period (2012-2019) and the "post-

pandemic" period (2020-2022). The results are shown in Figure 6 and Figure 7, respectively.

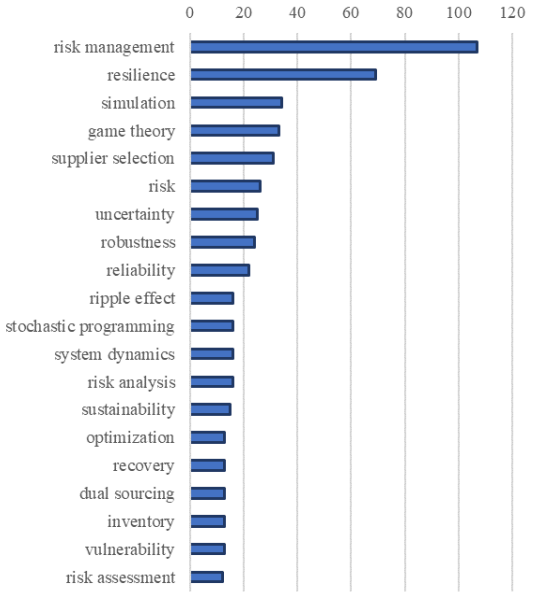

Figure 6. Frequency of appearance of the most relevant keywords in the years 2013-2019

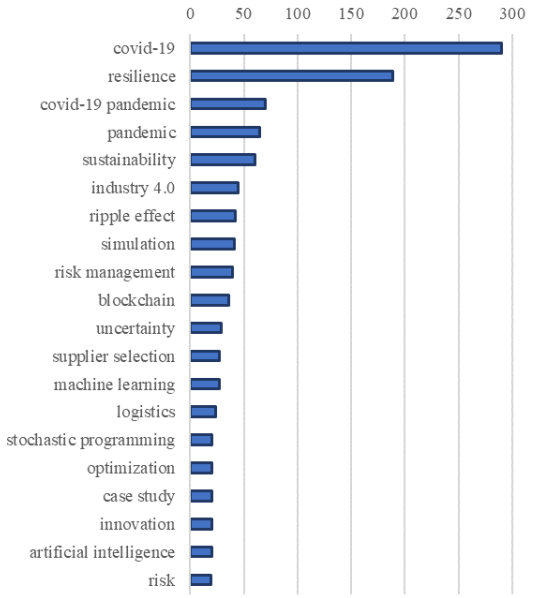

Figure 7. Frequency of appearance of the most relevant keywords in the years 2020-2022

Confirming the above, it can be observed that the concepts of *risk management* and *resilience* were present even before the pandemic. In the post-pandemic period, Industry 4.0, in part due to government restrictions, has assumed considerable importance. The increased presence of keywords such as *machine learning*, *digital twin* and *blockchain*, which increased their frequency in respect to the pre-pandemic period by 12.5 times, 4.7 times and 4.1 times respectively confirm this and highlight how these technologies are the ones on which researchers are focusing most of the attention. Moreover, keywords like *artificial intelligence*, *digital transformation* and *digital technologies* appears for the first time during the post-pandemic period. While other technologies and methodologies appear to have become less attractive from a research point of view: indeed, keywords like *risk management*, *risk analysis*, *game theory*, *information sharing* decreased their frequency of 63.6%, 66.7%, 56.2% and 45.5%, respectively.

The keyword *sustainability* has gained importance in the past few years, due to the increasing attention paid by the public to this topic. This demonstrates how the pandemic, together with the climate crises and natural catastrophes that have occurred much more frequently in the recent years, have raised awareness about the fragility of the ecosystems of the world.

IV. Conclusions

The study highlighted that disruptions tends to increase the scientific interest in the development of innovative resilient supply chain models. Downstream of the pandemic, in particular, a growing interest in the Industry 4.0 enabling technologies has emerged. Among them, those who are experiencing the greatest growth trend are *machine learning* and *artificial intelligence*. In conjunction with them, among the emerging keywords, *digital twin*, *digital technologies*, *digital transformation*, *sustainable development*, *operational performance* and *3D printing* have also experienced a significant increase in the frequency of appearance. These themes can therefore be considered as the main lines of research for the coming years. Some suggestions for future research topics are: (*i*) exploration of how real-time data, predictive analytics, and digital twins can help in identifying and mitigating supply chain disruptions, such as natural disasters, geopolitical events, and supplier failures; (*ii*) Analysis of the role of artificial intelligence, machine learning, and advanced analytics in demand forecasting, inventory optimization, and dynamic routing for efficient and flexible supply chain operations; (*iii*) study of the impact of digitalization and automation on resource utilization, energy efficiency, waste reduction, and ethical sourcing practices; (*iv*) Exploration of the impact of Industry 4.0 on the workforce in supply chain operations, on the changing skill requirements, on the training needs, and on the organizational structures resulting from the

adoption of advanced technologies, (*v*) Examination of the strategies for managing workforce transitions and ensuring successful human-machine collaboration; (*vi*) Investigation on the challenges and opportunities associated with integrating these technologies into existing supply chain systems.

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Appendix A. FIRST APPENDIX – FIGURES ON TWO COLUMNS

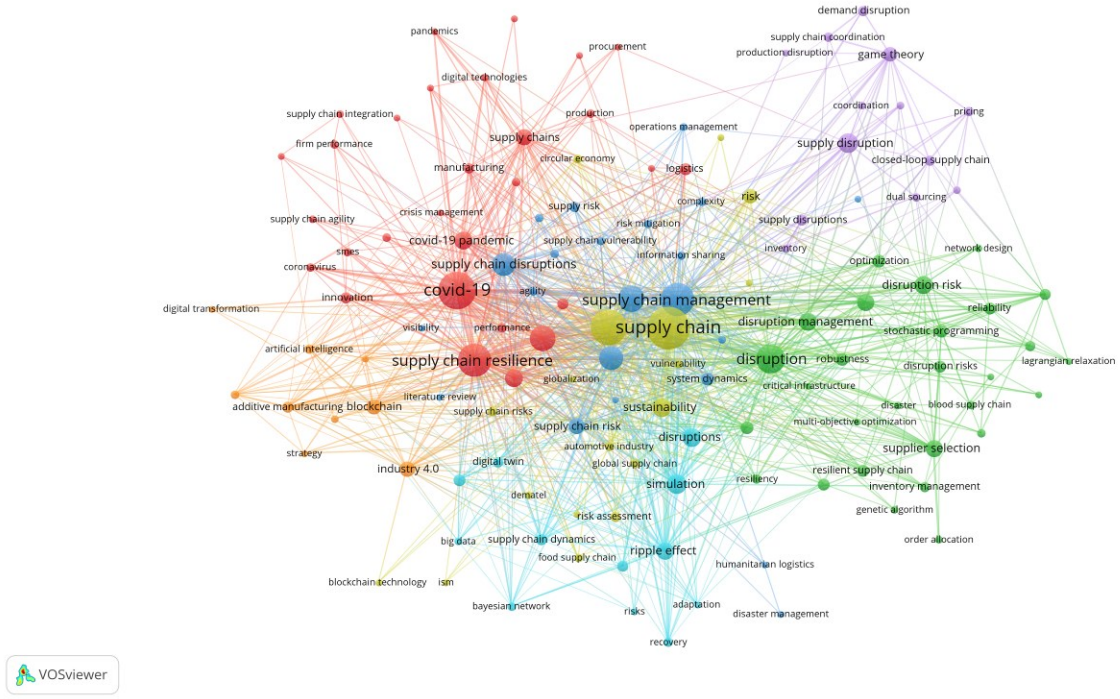

Figure 8. Network view of the keywords used at least 10 times in the papers selected for the analysis, highlighting the identified clusters of keywords with different colours