

Bibliometric Insights into Manufacturing Flexibility: Scholarly Output, Hot Topics, and Research Gap

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DOI: <https://dx.doi.org/10.47772/IJRISS.2025.909000688>

Received: 22 September 2025; Accepted: 28 September 2025; Published: 27 October 2025

ABSTRACT

This study presents a comprehensive bibliometric analysis of scholarly literature on “manufacturing flexibility” and “flexible manufacturing system” from 1985 to 2024. Based on 252 Scopus-indexed publications, the analysis conducted using VOSviewer and Bibliomagika uncovers key trends, citation structures, influential authors, and leading journals. With a total of 13,198 citations and an average of 52.37 citations per paper, the findings underscore the field’s sustained relevance, particularly in the context of Industry 4.0. Notable contributions by Gerwin (1993), Upton (1994), and Zhang et al. (2003) reflect the field’s conceptual and empirical maturity. The International Journal of Production Economics is identified as the most influential journal. Co-citation and network analyses reveal strong thematic and authorial coherence. While limited to Scopus and quantitative metrics, the study offers a foundational map of the field’s intellectual landscape. It provides valuable insights for scholars and practitioners, guiding future research directions in dynamic global manufacturing contexts.

Keywords: Bibliometric Analysis, Manufacturing Flexibility, Flexible Manufacturing System, BiblioMagika, VosViewer

INTRODUCTION

In today’s rapidly evolving industrial landscape, manufacturing flexibility has emerged as a critical capability for firms aiming to remain competitive, resilient, and innovative. Defined as the ability of a manufacturing system to respond efficiently to changes in product type, volume, and production processes, manufacturing flexibility is increasingly recognized as a strategic asset in dynamic and uncertain market environments (Zhang, Vonderembse, & Lim, 2003). The shift from rigid, mass production systems toward more adaptive, responsive production models has been driven by globalization, technological advancements, and heightened customer expectations (Vokurka & O’Leary-Kelly, 2000).

Over the past few decades, the concept of manufacturing flexibility has evolved significantly, with developments ranging from Flexible Manufacturing Systems (FMS) in the 1980s to more advanced strategies like agile, lean, and reconfigurable manufacturing in recent years (Sethi & Sethi, 1990; Moin et al., 2024). The ongoing Industry 4.0 revolution, marked by digital technologies such as IoT, artificial intelligence, automation, and robotics, has further enhanced the potential for real-time production adjustments, efficient resource use, and sustainable operations (Margherita & Braccini, 2020). These advancements underscore the role of flexibility not only in operational performance but also in fostering innovation, product customization, and long-term strategic differentiation (Castiglione et al., 2024).

Despite growing interest, the literature on manufacturing flexibility remains fragmented, with much of the focus centered on its general impact on operational performance. There is limited consensus on how specific dimensions such as machine, labour, material handling, and routing flexibility individually or collectively influence key outcomes like new product development, time-to-market, and sustainable competitive advantage (Yu & Lee, 2023; Awwad, Anouze, & Ndubisi, 2022). Furthermore, while many studies highlight the

theoretical importance of flexibility in manufacturing, empirical evidence remains mixed and context-dependent (Hong Loong et al., 2023).

Given these gaps, a systematic bibliometric analysis of manufacturing flexibility research is timely and necessary. Bibliometric methods enable the mapping of scholarly trends, the identification of influential publications and authors, and the detection of emerging research themes. By offering a comprehensive overview of the evolution, focus areas, and intellectual structure of the field, this study aims to inform future research directions and support the development of more robust and context-sensitive manufacturing strategies.

This paper consists of the following sections. Section 1 is devoted to the introduction. Section 2 explains the overview of the manufacturing flexibility literature based on previous research and the research objectives. Section 3 describes the methodology used to perform the bibliometric analysis, including the step-by-step process for retrieving documents from the Scopus database and using the VOSviewer and Bibliomagika software. Section 4 presents the results derived from both tools. Finally, Section 5 presents the conclusions and offers practical suggestions for future research and industrial applications.

LITERATURE REVIEW

The evolution of manufacturing flexibility (MF) has undergone significant transformations, beginning with the rigid mass production systems of the early 20th century, epitomized by Fordism, and transitioning to the adaptive and intelligent systems characteristic of Industry 4.0. While early manufacturing systems were optimized for standardized, high-volume outputs, by the 1960s and 1970s, the limitations of such models became evident as markets demanded greater responsiveness and product variety. This shift catalysed the emergence of more flexible approaches, such as batch production and job-shop systems. A pivotal turning point occurred in the 1980s with the development of Flexible Manufacturing Systems (FMS), integrating technologies such as Computer Numerical Control (CNC), robotics, and automated material handling to support rapid changeovers and reconfiguration. By the 1990s, scholarly discussions had expanded MF beyond shop-floor technologies to include dimensions such as mix, volume, and product flexibility, reflecting its growing complexity and strategic significance (Vokurka & O'Leary-Kelly, 2000).

In the 2000s, research on MF increasingly emphasized its integration with supply chain management and broader corporate strategies as global markets became more volatile and competitive. The advent of Industry 4.0 has further deepened this transformation, with digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and advanced robotics enabling real-time responsiveness, operational efficiency, and sustainability (Margherita & Braccini, 2020). Contemporary conceptualizations of MF extend beyond simple operational adjustments, framing it as a core dynamic capability that enables firms to adapt to uncertainty, exploit modularity and scalability, and achieve cost-effective customization (Habib et al., 2023; Castiglione et al., 2024; Rama Murthy et al., 2024).

Empirical evidence further demonstrates the operational and strategic benefits of MF. Studies show that flexibility reduces setup times, lowers inventory levels, and enhances resource utilization, thereby improving customer satisfaction and competitive positioning. For example, Castiglione et al. (2023) utilized simulation models to demonstrate that flexible systems consistently outperform conventional ones in volatile environments. Meanwhile, emerging technologies such as Additive Manufacturing (AM) have expanded flexibility into remanufacturing and small-batch customization (Hofmeester & Eyers, 2023).

In the context of Malaysia's Electrical and Electronics (E&E) industry, MF has become particularly critical given the sector's global integration, rapid technological cycles, and exposure to external shocks. The COVID-19 pandemic underscored this necessity, with firms possessing higher flexibility demonstrating stronger resilience in sustaining operations and financial stability during disruptions (Zahari et al., 2023). Recent research highlights the adoption of modular production designs and smart technologies in Malaysian firms to enhance responsiveness and customer-oriented customization (Yeap et al., 2024; Ang et al., 2024).

Taken together, the literature positions MF as both a technical and strategic imperative for firms navigating volatile and competitive environments. However, despite extensive scholarly attention, the field has developed across multiple streams, spanning operations research, production engineering, supply chain management, and strategic management. This fragmentation highlights the need for a systematic bibliometric analysis to map the intellectual landscape, identify dominant themes and influential works, and trace the evolution of research trajectories. Accordingly, this study employs bibliometric techniques to provide a structured overview of MF research, offering insights into its historical roots, contemporary developments, and future directions.

METHODOLOGY

This study employs a systematic bibliometric analysis to investigate the intellectual landscape and evolution of research on manufacturing flexibility. The methodological framework adopted in this research follows a structured and replicable process inspired by the guidelines proposed by Punj et al. (2021) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework introduced by Moher et al. (2009). The goal is to ensure methodological transparency and rigor in the identification, selection, and analysis of relevant literature.

Bibliometric analysis

Bibliometrics is "the application of mathematics and statistical methods to books and other media of communication" (Pritchard, 1969). According to Potter (1981), bibliometric measures publication patterns and written communications, and authorship modes. According to (Garfield et al., 1964; Liang & Liu, 2018; White & McCain, 1989), bibliometric analysis is the quantitative approach to analyze academic, it measures text and information and makes it possible to analyze published documents (Daim et al., 2006; Hall, 2011). This method is a popular method for uncovering trends in the research articles being studied (Ahmi & Mohamad, 2019). Additionally, it can be used in evaluating the quantity and quality of published material to monitor trends or patterns in a particular research area (Sweileh et al., 2017). The methodological framework adopted in this research follows a structured and replicable process inspired by the guidelines proposed by Punj et al. (2021) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework introduced by Moher et al. (2009). This process ensures methodological transparency and rigor in the identification, selection, and analysis of relevant literature, as depicted in Figure 1. Bibliometric analysis can also provide descriptive patterns of publications by domain, field, country, and period (Ho, 2007). Finally, bibliometric analysis can provide more detailed information regarding a publication, including the author, the keyword frequency, and citations (Rusly et al., 2019). Thus, the bibliometric method can reveal and analyze the impact of literature on each scientific discipline and help formulate policies for various studies, publishers' ratings, literature developments, collection developments, and other related policies.

Source and data collection

Bibliographic data for this study were sourced from the Scopus database on Friday, April 25th, 2025, at 9:46 AM. The dataset included metadata from 252 scholarly publications, encompassing information on authors, institutional affiliations, countries, and citation metrics. Scopus was selected due to its strong competitive advantage over other databases, as it is frequently used in academic studies (Harzing & Alakangas, 2016) and offers an extensive temporal coverage (Mongeon & Paul-Hus, 2016). The bibliometric analysis followed several established search procedures (Riera & Iborra, 2017). Specifically, the search query "manufacturing flexibility OR flexible manufacturing system" was applied to article titles, targeting publications from 1985 to 2025. Focusing on article titles enhanced the specificity and precision of the data retrieved (Aleixandre et al., 2015; Sweileh et al., 2017). Metadata was exported in CSV format for further processing. For analysis, tools such as Microsoft Excel and Bibliomagika (Aidi Ahmi, 2024) were utilized, while VOSviewer software was employed for data visualization. VOSviewer helps in identifying performance metrics and conducting term co-occurrence analyses, assuming that article keywords reliably reflect the content. The co-appearance of keywords within a single article indicates a thematic relationship. By examining the strength of associations between key terms from related publications, the evolution and thematic structure of research within the field can be effectively mapped (Zupic & Čater, 2015).

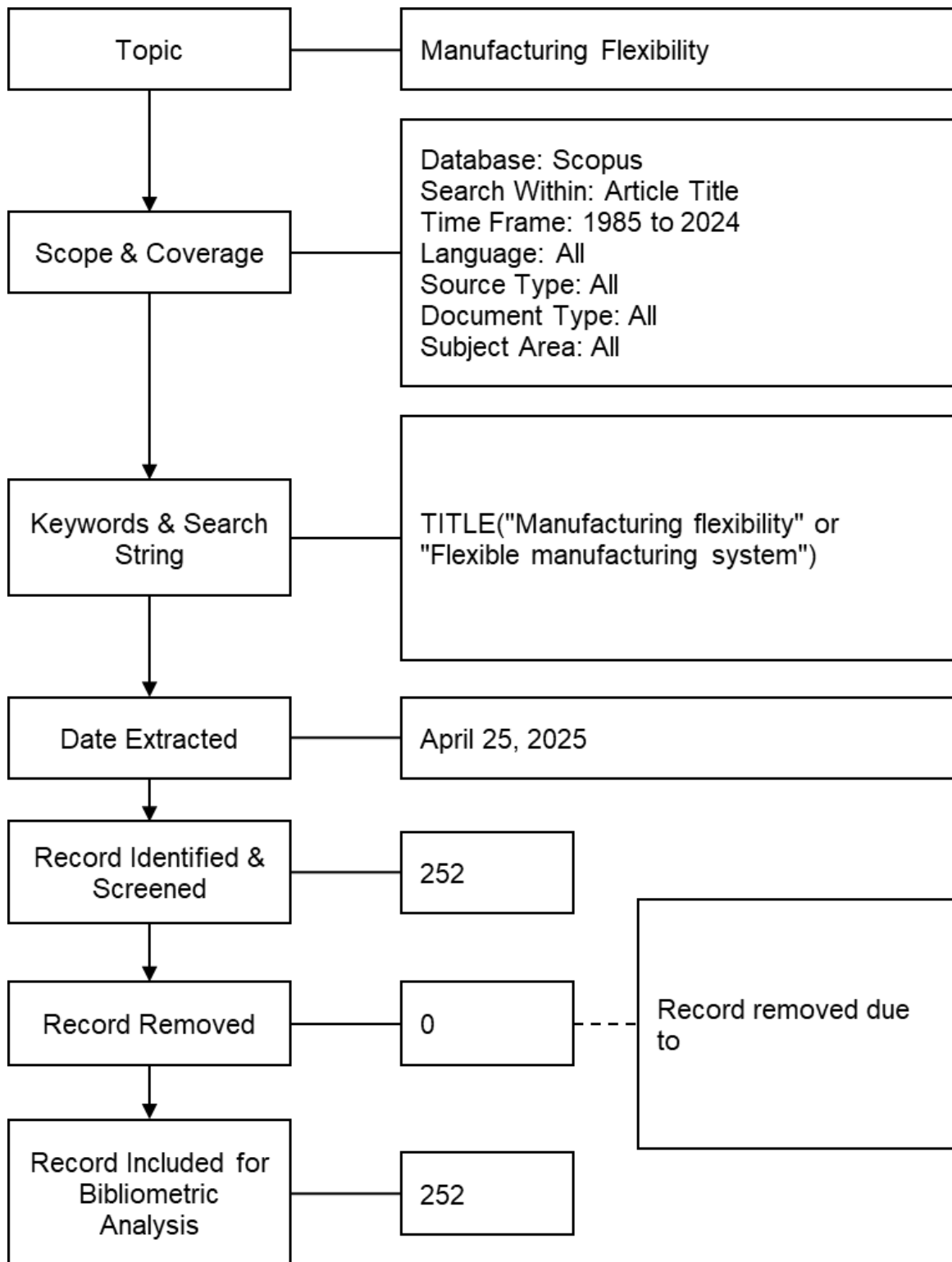


Figure 1: PRISMA Flow Diagram

RESULTS AND DISCUSSION

Document and Source Types

Table 1 presents the distribution of document types identified in the final dataset of 252 publications related to manufacturing flexibility. Most contributions fall under the category of journal articles, accounting for 194 documents or approximately 76.98% of the total. This predominance reflects the scholarly emphasis on disseminating research on manufacturing flexibility through peer-reviewed journal publications, which are typically considered rigorous and foundational within academic discourse.

Conference papers represent the second most frequent document type, with 40 occurrences comprising 15.87% of the dataset. This indicates a notable presence of preliminary or emerging research findings presented at academic and professional conferences. The inclusion of conference proceedings suggests that manufacturing flexibility remains a dynamic topic of discussion within the broader research community, where ongoing studies are shared before journal publication. Review articles constitute 3.97% of the total, with 10 documents. These reviews likely offer critical evaluations and syntheses of the literature, contributing to the theoretical development and consolidation of knowledge in the field. Book chapters account for a smaller portion, comprising six documents or 2.38%, possibly indicating interdisciplinary contributions or conceptual discussions embedded in broader edited volumes.

Finally, the dataset includes a limited number of less common document types: one note and one short survey, each representing 0.40% of the total. While marginally in frequency, these types contribute to the diversity of scholarly formats present in the field. Collectively, the distribution highlights the dominance of journal articles in shaping the academic landscape of manufacturing flexibility research, while also pointing to the relevance of other publication formats in enriching the discourse.

Table 1: Document Type

Document Type	Frequency	% (N=252)
Article	194	76.98
Conference Paper	40	15.87
Review	10	3.97
Book Chapter	6	2.38
Note	1	0.40
Short Survey	1	0.40
Total	252	100.00

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

The distribution of source types in the dataset, as summarized in Table 2, reveals that most publications on manufacturing flexibility have been disseminated through academic journals. Specifically, journal sources account for 206 out of the total 252 documents, representing 81.75% of the dataset. This dominance underscores the centrality of peer-reviewed journals in advancing and formalizing research in the field. It also reflects the scholarly community's preference for publishing rigorous, theory-driven, and empirically validated studies in well-established academic outlets.

Conference proceedings constitute the second most common source type, with 33 documents making up 13.10% of the total. This relatively substantial proportion signals the role of academic and professional conferences as key venues for the presentation of novel research, often in its preliminary stages. Conferences provide a platform for researchers to engage in scholarly dialogue, receive feedback, and disseminate new ideas, which may later be developed into journal publications.

Other source types appear less frequently but contribute to the diversity of literature. Book series account for seven documents, representing 2.78% of the total. These contributions often appear in edited volumes that bring together thematic insights across multiple chapters. Books and trade publications each represent 1.19% of the dataset, with three documents each. Although limited in number, these sources may offer practitioner-oriented perspectives or in-depth explorations that complement the findings presented in academic journals

and conference proceedings. Overall, the dominance of journals and conference proceedings suggests that the discourse on manufacturing flexibility is primarily shaped within formal academic environments, while also allowing room for alternative publication formats that can provide broader or more specialized insights.

Table 2: Source Type

Source Type	Frequency	% (N=252)
Journals	206	81.75
Conference Proceedings	33	13.10
Book Series	7	2.78
Books	3	1.19
Trade Publications	3	1.19
Total	252	100.00

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Year of Publications - Evolution of Published Studies

The table provides a detailed longitudinal overview of the publication and citation patterns related to manufacturing flexibility from 1985 to 2024. Over these 40 years, a total of 252 publications (TP) were identified, offering insights into both the volume and influence of scholarly output in the field. Temporal distribution reveals a gradual increase in research interest, with a noticeable rise in the number of publications from the mid-1990s onwards. For example, earlier years such as 1985 and 1987 each contributed only one publication, whereas subsequent years, particularly from 1996 through the early 2000s, show an upward trend, including peaks in publication counts in 1996, 1998, 2005, 2014, and 2022, each with 10 or more publications. The year 2014 marks the highest single-year publication output with 11 papers (4.37% of the total dataset).

The number of cited publications (NCP) follows a similar but not identical pattern, reflecting the scholarly impact of specific contributions. For instance, the early 1990s contain several highly cited works, particularly in 1992 (441 total citations), 1993 (1,074 citations), and 1994 (779 citations), despite relatively low publication counts. This highlights the foundational influence of research from this period, where fewer but more impactful studies were published.

Citation per publication (C/P) and citation per cited publication (C/CP) offer further granularity into scholarly influence. Notably, publications in 1994 and 1993 recorded the highest C/P values of 779.00 and 214.80, respectively, suggesting these years hosted seminal works with lasting academic relevance. In contrast, more recent years, such as 2021 through 2024, show significantly lower citation averages, which is expected due to the limited time for citations to accumulate.

The h-index and g-index values across the years offer additional dimensions of research performance. Years with both high productivity and impactful papers, such as 1999, 2000, 2005, and 2014, exhibit relatively higher h- and g-indices, indicating consistent citation across multiple publications rather than isolated peaks. For example, the year 2000, with 9 publications and a total of 1,130 citations, achieves an h-index of 8 and a g-index of 9, reflecting both breadth and depth in scholarly influence. In summary, the temporal analysis illustrates maturation and sustained scholarly interest in manufacturing flexibility. The field has evolved from a few foundational papers in the 1980s to a more established and active domain in the 2000s and beyond, with periods of both high productivity and landmark contributions. While the most recent years (post-2020) exhibit lower citation counts due to recency, their volume suggests a continued and possibly growing interest in the topic.

Table 3: Year of Publications

Year	TP	% (N=252)	NCP	TC	C/P	C/CP	h-index
1985	1	0.40	1	1	1	1	1
1987	1	0.40	1	138	138	138	1
1988	3	1.19	1	7	2.33	7	1
1989	2	0.79	2	142	71	71	2
1990	2	0.79	1	40	20	40	1
1991	5	1.98	5	166	33.20	33.20	5
1992	6	2.38	6	441	73.50	73.50	4
1993	5	1.98	5	1074	214.80	214.80	4
1994	1	0.40	1	779	779.00	779.00	1
1995	4	1.59	4	327	81.75	81.75	3
1996	10	3.97	8	537	53.70	67.13	6
1997	2	0.79	2	5	2.50	2.50	1
1998	10	3.97	6	671	67.10	111.83	5
1999	7	2.78	7	1237	176.71	176.71	7
2000	9	3.57	9	1130	125.56	125.56	8
2001	6	2.38	4	181	30.17	45.25	3
2002	9	3.57	8	256	28.44	32.00	5
2003	6	2.38	5	693	115.50	138.60	4
2004	5	1.98	4	299	59.80	74.75	3
2005	10	3.97	9	437	43.70	48.56	8
2006	9	3.57	9	520	57.78	57.78	8
2007	8	3.17	8	155	19.38	19.38	6
2008	8	3.17	7	181	22.63	25.86	6
2009	9	3.57	9	255	28.33	28.33	6
2010	6	2.38	4	203	33.83	50.75	4
2011	8	3.17	7	265	33.13	37.86	6
2012	7	2.78	6	501	71.57	83.50	5
2013	8	3.17	7	341	42.63	48.71	4
2014	11	4.37	10	467	42.45	46.70	7
2015	10	3.97	7	177	17.70	25.29	6
2016	6	2.38	6	269	44.83	44.83	5
2017	7	2.78	4	505	72.14	126.25	4
2018	7	2.78	7	339	48.43	48.43	7
2019	9	3.57	9	134	14.89	14.89	6
2020	7	2.78	7	123	17.57	17.57	6
2021	7	2.78	5	25	3.57	5.00	3
2022	10	3.97	8	123	12.30	15.38	4
2023	6	2.38	6	51	8.50	8.50	2
2024	5	1.98	2	3	0.60	1.50	1
Total	252	100.00					

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

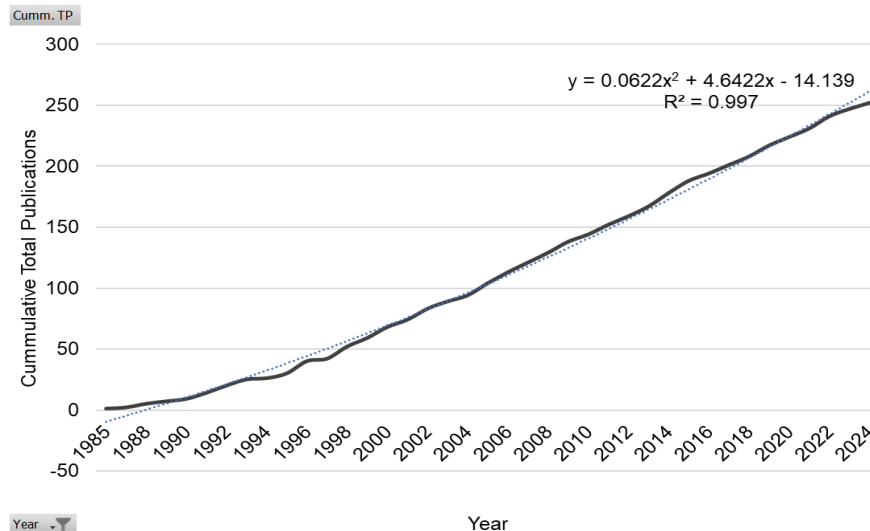


Figure 2: Cumulative Growth of Publications Over Time (1997-2023)

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Languages of Documents

The language distribution of the publications, as outlined in the table, indicates a strong predominance of English-language scholarship in the field of manufacturing flexibility. Of the 252 documents analyzed, 247 were published in English, comprising 98.02% of the total. This overwhelming majority highlights English's status as the primary medium for academic communication in the field, facilitating global dissemination, accessibility, and citation of scholarly work.

The remaining publications are distributed across a few other languages, each representing a minimal portion of the dataset. Specifically, there are two documents in German (0.79%) and one document each (0.40%) in French, Malay, Moldavian, Moldovan, Portuguese, and Romanian. These non-English publications reflect the geographically diverse origins of research on manufacturing flexibility but also underscore the limited impact and visibility of non-English scholarship within mainstream academic discourse, particularly in databases such as Scopus.

Overall, the dominance of English suggests that researchers aiming to reach a broad international audience and maximize scholarly impact generally publish in English-language journals. At the same time, the presence of multilingual contributions, though minimal, points to the global relevance of the topic and its exploration in localized academic contexts.

Table 4: Languages Used for Publications

Language	Frequency*	% (N=252)
English	247	98.02%
German	2	0.79%
French	1	0.40%
Malay	1	0.40%
Moldavian	1	0.40%
Moldovan	1	0.40%
Portuguese	1	0.40%
Romanian	1	0.40%
Total	252	100.00

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Subject Area

The subject area classification of the 252 publications on manufacturing flexibility reveals the multidisciplinary nature of the field, though certain disciplines clearly dominate. The highest concentration of research is situated within the domain of Business, Management and Accounting, which accounts for 154 publications, or 61.11% of the total. This prominence reflects the managerial and strategic orientation of manufacturing flexibility, particularly its relevance to operations management, production planning, and supply chain optimization. Closely following is the field of Engineering, with 150 publications (59.52%), indicating the technical and process-oriented aspects of the topic. The strong representation of engineering-related research underscores the importance of manufacturing systems design, automation, and industrial innovation in advancing flexible manufacturing capabilities.

Decision Science is another major contributor, encompassing 104 documents or 41.27%. This highlights the analytical and modelling frameworks frequently employed to address decision-making under uncertainty, resource allocation, and optimization problems in manufacturing environments. Computer Science, represented by 74 publications (29.37%), also plays a significant role, reflecting the increasing integration of digital technologies, simulation, artificial intelligence, and data analytics into flexible manufacturing systems. Additionally, though smaller, contributions emerge from fields such as Mathematics (6.75%), Economics, Econometrics and Finance (5.56%), and Materials Science (3.57%). These areas provide theoretical modelling, economic evaluations, and material-level considerations that complement the core engineering and managerial discourse.

More peripheral but still notable areas include Social Sciences, Chemistry, Physics and Astronomy, Chemical Engineering, and Pharmacology, Toxicology and Pharmaceuticals, each contributing between 1.19% and 2.38% of the publications. These entries suggest niche or interdisciplinary intersections where manufacturing flexibility might be relevant, such as in laboratory-based production environments or cross-disciplinary innovation contexts. Smaller representations are also observed in Arts and Humanities, Energy, Environmental Science, and Multidisciplinary studies. Although these areas account for less than 1% each, their inclusion signifies the potential expansion of the topic into broader societal, environmental, or integrative domains. In sum, while the majority of research on manufacturing flexibility resides within business and engineering-oriented disciplines, the field is inherently interdisciplinary, drawing on a wide range of methodological and conceptual approaches. This diversity reinforces the complexity of the topic and its applicability across various sectors of research and practice.

Table 5: Subject Area

Subject Area	Frequency	% (N=252)
Business, Management, and Accounting	154	61.11%
Engineering	150	59.52%
Decision Science	104	41.27%
Computer Science	74	29.37%
Mathematics	17	6.75%
Economics, Econometrics, and Finance	14	5.56%
Material Science	9	3.57%
Social Science	6	2.38%
Chemistry	4	1.59%
Physics and Astronomy	4	1.59%
Chemical Engineering	3	1.19%
Pharmacology, Toxicology, and Pharmaceuticals	3	1.19%
Arts and Humanities	2	0.79%
Energy	2	0.79%

Multidisciplinary	2	0.79%
Environmental Science	1	0.40%
Total	252	100

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Most Active Source Titles

Table 6 presents the most active source titles contributing to the body of knowledge on manufacturing flexibility, highlighting the dominance of a select number of specialized journals in shaping this field. The International Journal of Production Research emerges as the leading outlet, publishing 22 documents (8.73%), which underscores its central role in advancing research on production systems, manufacturing strategies, and operational flexibility. Following closely, the Journal of Manufacturing Technology Management contributes 14 publications (5.56%), reflecting its emphasis on the managerial and technological aspects of flexible manufacturing systems and their integration into industrial practices. Similarly, the Journal of Operations Management demonstrates strong engagement with 13 publications (5.16%), focusing on strategic operations, efficiency, and flexibility in production planning.

The International Journal of Operations and Production Management accounts for 10 documents (3.97%), while the International Journal of Production Economics and the Global Journal of Flexible Systems Management each contribute 9 documents (3.57%). These journals collectively reflect the economic, managerial, and systems-oriented approaches underpinning manufacturing flexibility research. Furthermore, broader operations and decision-making perspectives are evident in contributions from the European Journal of Operational Research (8 documents, 3.17%) and the Proceedings of the Annual Meeting of the Decision Sciences Institute (6 documents, 2.38%). The latter, in particular, highlights that scholarly discourse on manufacturing flexibility is not limited to journals but also extends to conference proceedings, where new insights and emerging methodologies are often first presented.

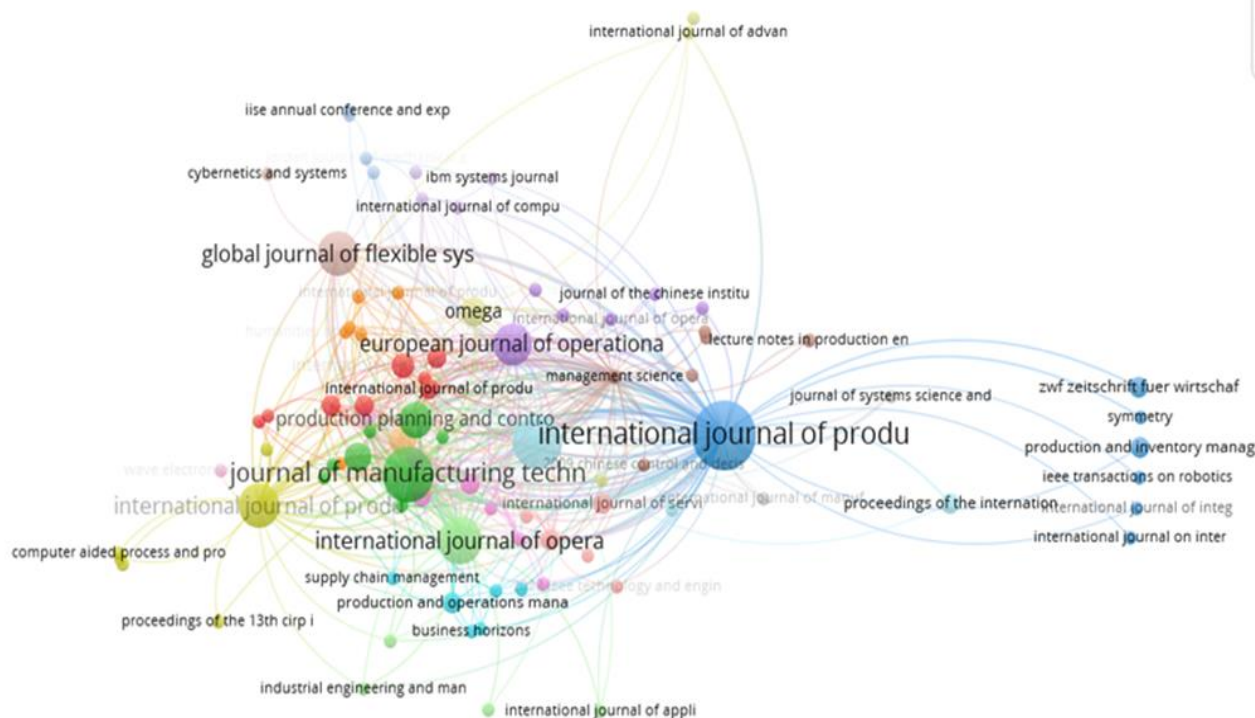
Other notable contributions come from Production Planning and Control (6 documents, 2.38%), Integrated Manufacturing Systems (4 documents, 1.59%), Omega (4 documents, 1.59%), and the International Journal of Flexible Manufacturing Systems (4 documents, 1.59%). Although smaller in output, these journals are highly specialized and provide platforms dedicated to production system design, optimization, and flexibility. Additional outlets such as the International Journal of Industrial and Systems Engineering (3 documents, 1.19%), Business Process Management Journal (2 documents, 0.79%), Decision Sciences (2 documents, 0.79%), and Benchmarking (2 documents, 0.79%) further demonstrate the interdisciplinary reach of manufacturing flexibility research, extending into areas such as process management, performance benchmarking, and organizational strategy.

Overall, the distribution of source titles suggests that while a handful of journals dominate in terms of research volume, the topic of manufacturing flexibility spans across a diverse array of publication outlets. This reflects its inherently interdisciplinary character and its relevance to both theoretical exploration and practical applications in production, operations, and organizational management.

Table 6: Most Active Source Title

Source Title	No. of Documents	%
International Journal of Production Research	22	8.73
Journal of Manufacturing Technology Management	14	5.56
Journal of Operations Management	13	5.16
International Journal of Operations and Production Management	10	3.97
International Journal of Production Economics	9	3.57
Global Journal of Flexible Systems Management	9	3.57
European Journal of Operational Research	8	3.17

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)



Source: VOSViewer

Authorship

The analysis of authorship patterns in the manufacturing flexibility literature reveals important insights into the collaborative and scholarly landscape of the field. Table 7 presents the distribution of the number of authors per document among the 252 publications included in this bibliometric study. The most common authorship configuration involves two authors, accounting for 34.92% of the total documents. This suggests a strong tendency toward collaborative research, likely due to the interdisciplinary and complex nature of manufacturing flexibility studies. Single-author papers constitute 21.03% of the documents, indicating a significant proportion of individual contributions. Papers with three authors represent 24.60%, while documents with four or more authors become progressively less common, reflecting a typical distribution in engineering and management sciences. Notably, a small number of papers were co-authored by five (5.16%), six (0.40%), or more authors, with one publication listing as many as thirteen contributors, which may reflect large-scale, multi-institutional collaborations or systematic reviews. Additionally, one conference review document had no author listed, likely due to specific publication formatting or database indexing practices. Overall, this distribution underscores the predominance of small to mid-sized research teams within the field.

Table 8 identifies the most productive authors contributing to the field of manufacturing flexibility. Mishra, R. emerges as the leading contributor, authoring nine documents, which represent 3.57% of the total corpus. A cluster of other influential scholars, including Chang, S.C., Ganapathy, L., and Pundir, A.K., each contributed five documents, making up 1.98% of the dataset, respectively. Several additional authors, such as Beach, R., Malhotra, M.K., Purwanto, U.S., and Sheu, C., also stand out for having published four articles each (1.59%). A broader group of contributors, including Das, A., Iqbal, M., and Olhager, J., among others, authored three documents each (1.19%). The presence of multiple authors with relatively modest publication counts typically ranging from three to five documents suggests a distributed authorship landscape rather than dominance by a few prolific individuals. This pattern is indicative of a healthy and diverse academic community where knowledge is contributed from various geographic regions and institutional contexts. It also highlights the potential for collaborative networks and further research opportunities within this domain.

Table 7: Number of Author(s) per Document

Author Count	Frequency	% (N=252)
0	1	0.40
1	53	21.03
2	88	34.92
3	62	24.60
4	30	11.90
5	13	5.16
6	1	0.40
7	2	0.80
8	1	0.40
9	1	0.40
13	1	0.40
Total	252	100.00

*Conference review document. No author is listed.

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Table 8: Most Productive Authors

Author's Name	No. of Documents	Percentage (%)
Mishra, R.	9	3.57%
Chang, S.C	5	1.98%
Ganapathy, L.	5	1.98%
Pundir, A.K.	5	1.98%
Beach, R.	4	1.59%
Malhotra, M.K.	4	1.59%
Purwanto, U.S.	4	1.59%
Sheu, C.	4	1.59%
Sushil.	4	1.59%
Das, A.	3	1.19%
Iqbal, M.	3	1.19%
Khamba, J.S.	3	1.19%
Khan, M.M.A.	3	1.19%
Kiran, R.	3	1.19%
Koste, L.L.	3	1.19%
Lin, R.J.	3	1.19%
Moin, C.J.	3	1.19%
Muhlemann, A.P.	3	1.19%
Oberoi, J.S.	3	1.19%
Ojha, D	3	1.19%
Olhager, J	3	1.19%
Paterson, A.	3	1.19%
Price, D.H.R.	3	1.19%
Rogers, P.P.	3	1.19%
Sharma, R.R.K.	3	1.19%

Source: Generated by the author(s) using biblioMagika® (Ahmi, 2024)

Keyword Co-occurrence

The keyword co-occurrence analysis using VOSviewer figure 4 reveals the intellectual structure of manufacturing flexibility research by mapping frequently associated terms into clusters. The visualization highlights several thematic groups that reflect the evolution and diversification of research in this domain. The largest cluster, represented in green, centers on manufacturing flexibility and its connection to manufacturing strategy, firm performance, dynamic capabilities, and environmental uncertainty. This cluster demonstrates that flexibility is not merely a technical construct but is increasingly studied as a strategic capability that enables firms to adapt to uncertainty and enhance competitive performance. The red cluster is closely tied to industrial management, supply chain management, customer satisfaction, and product design, highlighting the role of flexibility in meeting customer needs and achieving supply chain responsiveness. This suggests that research has moved from plant-level studies to broader organizational and inter-organizational contexts, linking flexibility with marketing, managerial decision-making, and supply chain agility.

The blue cluster emphasizes production control, scheduling, operations research, and strategic planning, reflecting the traditional engineering and operations management roots of manufacturing flexibility. These studies focus on problem-solving approaches, simulation models, and optimization techniques to improve efficiency and responsiveness within production systems. Another significant theme is represented by the light blue cluster, which focuses on specific flexibility dimensions such as machine flexibility, routing flexibility,

and volume flexibility, as well as research methods like case studies and surveys. This cluster highlights the operational-level investigations into how different types of flexibility can be developed, measured, and applied within manufacturing environments. Finally, the yellow cluster connects terms like management, commerce, manufacturing firms, and managers, bridging managerial practices with operational realities. This indicates the interdisciplinary nature of the field, with contributions from business, engineering, and decision sciences converging on the topic.

Overall, the thematic mapping illustrates the progression of manufacturing flexibility research from its early technical focus on scheduling, simulation, and machine-level adaptability, toward strategic considerations such as supply chain agility, customer satisfaction, and firm performance. More recently, the integration of dynamic capabilities and sustainability reflects the field's expansion into future-oriented areas, demonstrating that flexibility has become a critical enabler of resilience and competitiveness in an increasingly volatile environment.

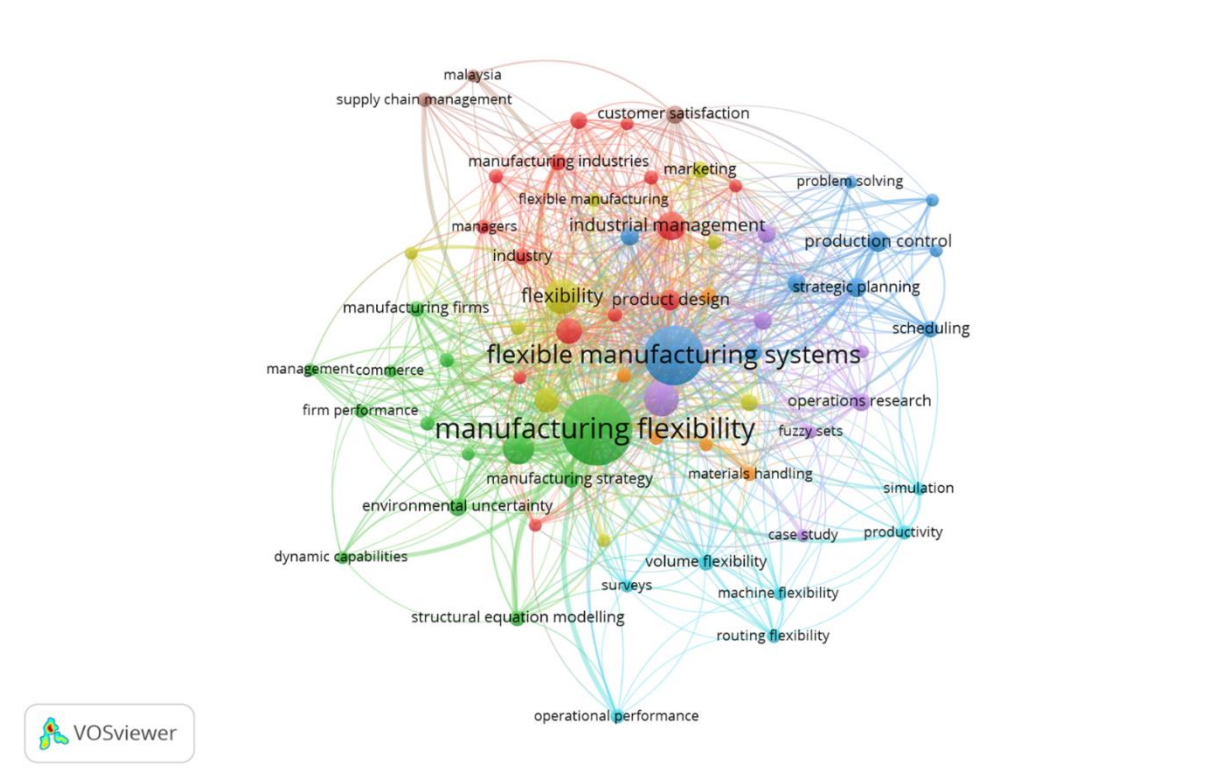


Figure 4: Network visualization map from keyword co-occurrence

Source: VOSViewer

CONCLUSION

Based on the comprehensive bibliometric analysis conducted in this study, it is evident that research on manufacturing flexibility has undergone substantial evolution over the past four decades. The field has transitioned from foundational theoretical explorations to empirical investigations, reflecting growing complexity and relevance, particularly in the context of Industry 4.0 and dynamic global markets. Through the examination of 252 documents retrieved from the Scopus database between 1985 and 2024, this study highlights the increasing scholarly interest in manufacturing flexibility, underscored by a total of 13,198 citations and an average of 52.37 citations per paper. The citation patterns reveal a well-established academic discourse, supported by influential contributions from key scholars such as Gerwin (1993), Upton (1994), and Zhang et al. (2003), whose works continue to serve as cornerstones for ongoing research.

The findings of this study contribute to the literature by offering a structured overview of the intellectual landscape of manufacturing flexibility through various bibliometric indicators, including author productivity,

citation metrics, and source journal impact. The network visualization maps further revealed strong interconnections among prominent journals such as the International Journal of Production Economics, Journal of Manufacturing Technology Management, and European Journal of Operational Research, indicating concentrated scholarly activity within specific publication outlets. Moreover, the identification of highly productive authors and frequently cited articles provides valuable insight into the key thought leaders and landmark studies that have shaped the field. The thematic analysis also highlights the multidimensional and interdisciplinary nature of the field, with contributions spanning engineering, business, operations research, and decision sciences. This cross-disciplinary engagement underscores that manufacturing flexibility is not only a technical concept rooted in production systems but also a strategic capability linked to supply chain agility, customer satisfaction, and organizational resilience.

Importantly, the persistence of highly cited early works demonstrates their enduring influence in shaping subsequent research directions. For instance, Gerwin's (1993) exploration of flexibility as a competitive weapon, Upton's (1994) framework on the dimensions of flexibility, and Zhang et al.'s (2003) empirical validation of flexibility-performance linkages continue to provide the theoretical and methodological foundations upon which newer studies are built. These foundational works have helped shift the discourse from machine- and process-level analyses toward broader strategic considerations, such as integration with supply chain management, dynamic capabilities, and digital transformation. Despite these contributions, the study is subject to certain limitations. The analysis was confined to the Scopus database, which, although comprehensive, may exclude relevant literature indexed in other databases such as Web of Science or Google Scholar. Additionally, the reliance on bibliometric tools such as VOSviewer and Bibliomagika, while effective in mapping trends and patterns, may not fully capture the nuanced theoretical or methodological depth of individual studies. Furthermore, the citation data does not distinguish between positive and critical citations, potentially overstating the perceived impact of certain works.

Looking ahead, the implications of this study point to several promising directions for future research. Scholars are encouraged to undertake content-based reviews to complement bibliometric findings, thereby providing richer qualitative insights into the evolving themes and conceptual frameworks within manufacturing flexibility. Expanding the scope to include interdisciplinary databases and employing altimetric indicators could also offer a more holistic understanding of how research on manufacturing flexibility is disseminated and utilized across academic and industrial spheres. Future studies should also explore emerging areas such as artificial intelligence, digital twins, and sustainable manufacturing practices, which are increasingly shaping how firms achieve and leverage flexibility. Sector-specific analyses, particularly in industries like electronics, automotive, and healthcare, could provide further clarity on how flexibility is operationalized in practice. Overall, this study demonstrates that manufacturing flexibility remains a vibrant and interdisciplinary research area, one that continues to evolve in response to technological advances, market volatility, and sustainability imperatives.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Ministry of Higher Education of Malaysia for their generous support under the Fundamental Research Grant Scheme (FRGS), grant number FRGS/1/2023/SS01/UTEM/02/3. This support was instrumental in enabling the successful completion of this research. The research was also funded by the Kesidang Scholarship.

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