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Evolution and impact of reliability model research : A bibliometric analysis of growth, regional trends, and emerging themes

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Reliability modelling has become increasingly important in engineering, software systems, infrastructure management, and artificial intelligence applications due to the growing complexity and interconnectedness of modern systems. Despite the rapid expansion of reliability-related research, a comprehensive bibliometric understanding of the field's intellectual structure, thematic evolution, and global collaboration patterns remains limited. This study presents a detailed bibliometric analysis of reliability model research from 1989 to 2024, using data from 2,037 scholarly records indexed in the Web of Science database. It reveals a steady annual growth rate of 10.37 percent, showing the increasing importance of reliability research across academic and industrial sectors. With the help of tools like Bibliometrix in R and VOSviewer, the study maps collaboration networks, key research themes, and emerging trends. The focus of research has expanded from traditional topics such as system failures and fault tolerance to modern concerns like software reliability, predictive modelling, and the use of artificial intelligence in optimization. International collaboration, particularly among China, the United States, India, and Australia, has played a vital role in shaping a more global and diverse research landscape. This study also connects reliability research with the United Nations Sustainable Development Goals, highlighting contributions to clean energy, smart systems, and resilient infrastructure. This work will benefit researchers, engineers, and policymakers by offering a clear direction for future studies that can improve system safety, performance, and societal resilience.

Keywords: Reliability model, Statistical reliability, Optimization techniques, Systems failures, Software reliability.

Highlights:

- Reliability research has seen a steady 10.37% annual growth boom.
- Powerhouses like China, the US, and EU are driving global synergy.
- AI, IoT & smart systems now headline the reliability research wave.
- Studies fuel big goals—clean energy & resilient cities shine bright.
- RESS stands tall as the gold standard in reliability publications

1. Introduction

Reliability refers to the likelihood that a system or its individual components will perform their intended functions correctly under specified conditions for a defined period of time [1]. This concept is fundamental throughout a product's entire lifecycle, from initial design and manufacturing to operation, maintenance, and eventual retirement [2]. Reliability modelling plays a vital role in assessing, predicting, and improving system dependability by estimating how well a system can continue to function as expected over time [3]. As a result, reliability models are widely applied across diverse fields such as mechanical and electrical engineering, computer science, transportation, healthcare, and risk management [4]. These models serve as essential tools for minimizing failure risks, improving system performance, and enhancing safety and resilience [5]. With modern systems becoming increasingly complex and interconnected, reliability modelling acts as a crucial link between theoretical concepts and practical implementation, supporting informed decision-making in system design, maintenance scheduling, and resource allocation [6].

The development of reliability modelling has closely followed technological progress. Early models were largely based on classical statistical techniques, but over time they have evolved to incorporate advanced computational approaches, including machine learning and artificial intelligence, to better address the complexities of modern systems [7]. Despite these advancements, traditional statistical reliability models remain highly relevant, particularly in predicting failures and supporting decisions related to design optimization, maintenance planning, and quality assurance in sectors such as manufacturing, healthcare, engineering, and finance [8], [9]. In software reliability analysis, Bayesian approaches have gained prominence due to their ability to model uncertainty effectively [10]. These models often use piecewise constant failure rates, martingale processes, and Markov chain sampling techniques to provide more accurate failure predictions [11]. Additionally, time-dependent stress–strength models have enhanced conventional reliability assessments by accounting for changes in system strength and external stresses over time, frequently employing probability distributions such as exponential, gamma, or Weibull [12].

To overcome the limitations of purely probabilistic methods, universal reliability models have been introduced that combine random variables with fuzzy sets and possibility theory [13]. This integration improves the applicability of reliability analysis in real-world

situations where uncertainty and imprecision are unavoidable [14]. At the same time, the importance of software reliability evaluation has increased significantly, as failures in software-intensive systems can lead to severe and widespread consequences. Recent advancements in this area include deep learning-based reliability models, which use optimized activation functions and specialized reliability functions to achieve higher predictive accuracy compared to traditional methods [15].

Reliability remains a critical factor across numerous applications, including medical diagnostics, infrastructure, manufacturing, and financial systems [5], [16], [17]. Commonly used performance indicators such as survival probability, mean time to failure, availability, and failure rate are standard benchmarks for evaluating system effectiveness [7]. Dynamic reliability models further enrich the field by illustrating how hazard rates change over time, allowing analysts to differentiate between degrading and non-degrading failure behaviours [18].

Table 1
Comparison of Previous Review Studies and the Present Study

Study	Research Focus	Methodology/ Dataset	Major Limitation
Bhamare et al. [19]	Evolution of reliability engineering	Narrative review	Does not provide bibliometric or science-mapping analysis
Zio [2]	Challenges in reliability engineering and uncertainty analysis	Conceptual review	Limited assessment of research trends and thematic development
Martyushev et al. [8]	Reliability prediction in technical and transport systems	Systematic review	Restricted to specific application domains
Payette and Abdul-Nour [4]	Machine learning applications in reliability engineering	Review study	Focuses mainly on AI-related reliability research
Recent domain-specific reviews [20], [21]	Predictive maintenance, Industry 4.0, software reliability, and fault diagnosis	Narrative/Systematic reviews	Limited analysis of specific domain like machine learning and its application
Present Study	Global reliability model research (1989–2024)	Bibliometric analysis of 2,037 Web of Science publications using Bibliometrix and VOSviewer	Strength: Provides an integrated assessment of publication trends, influential contributors, collaboration networks, citation structures, thematic evolution, and emerging research themes

As reliability engineering continues to evolve, it adapts to the growing complexity of systems and rapid technological change, offering robust frameworks that enhance performance, safety, and resilience across industries (Figure 1) [19]. As summarized in Table 1, existing review studies on reliability engineering have primarily focused on theoretical developments, methodological advances, or specific application areas. Although these reviews have enhanced understanding of reliability related concepts and techniques, they provide limited insight into the overall evolution and intellectual structure of reliability model research. In particular, comprehensive analyses of publication trends, citation impact, collaboration networks, and thematic development remain scarce. To bridge this gap, the present study conducts a bibliometric analysis of 2,037 publications indexed in the Web of Science database from 1989 to 2024. Using Bibliometrix in RStudio and VOSviewer, the study examines publication growth, influential journals, leading authors, institutional contributions, international collaborations, citation patterns, and thematic evolution. By adopting a science-mapping approach, this research offers a holistic perspective on the development of reliability model research and identifies emerging directions for future investigation. Such analyses support future research directions, encourage interdisciplinary collaboration, and help practitioners adopt effective tools and methodologies.

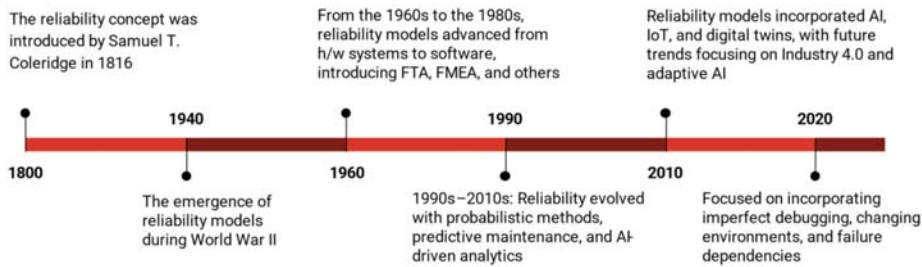


Figure 1
Historical Development of Reliability Model [19], [22]

2. Datasets and Research Methods

To comprehensively map and analyse the literature on reliability models, dependability models, and fault tolerance models, a systematic bibliometric approach was adopted. This methodology integrates a well-defined query formulation, an exhaustive database search, strict screening criteria, and advanced bibliometric techniques to ensure reproducibility and high-quality insights. The following sections describes every step of our method, as outlined in Figure 2.

2.1 Query formulation and data collection

The literature search began with the query TS = (“Reliability model”) OR TS = (“Dependability Model”) OR TS = (“Fault Tolerance Model”) in Web of Science database.

Searching titles, abstracts, and keywords yielded 2,154 records, ensuring comprehensive coverage of foundational and emerging research in reliability and fault tolerance [23].

2.2 Screening Process and Document Selection

The initial dataset was refined using a structured screening process based on clear inclusion and exclusion criteria. Publications indexed in the Web of Science database were considered for inclusion. The dataset was limited to English-language documents classified as articles, review papers, proceedings papers, early-access publications, and notes. Additionally, only publications published between 1989 and 2024 that primarily addressed reliability models, reliability engineering, dependability modelling, fault-tolerance approaches, or related reliability assessment methods were retained.

Several categories of records were excluded during the screening stage, including retracted publications, duplicate entries, non-English documents, and incomplete records from 2025. In addition, studies were excluded when the term “reliability” was mentioned only as a secondary concept rather than serving as the main subject of investigation. Records were considered outside the scope of this study if they lacked a substantial connection to reliability modelling, fault tolerance, or dependability analysis, or if the terminology was used in contexts unrelated to reliability research. After applying these criteria, the dataset was reduced from 2,154 to 2,037 documents, resulting in the formulation of the final query as follows:

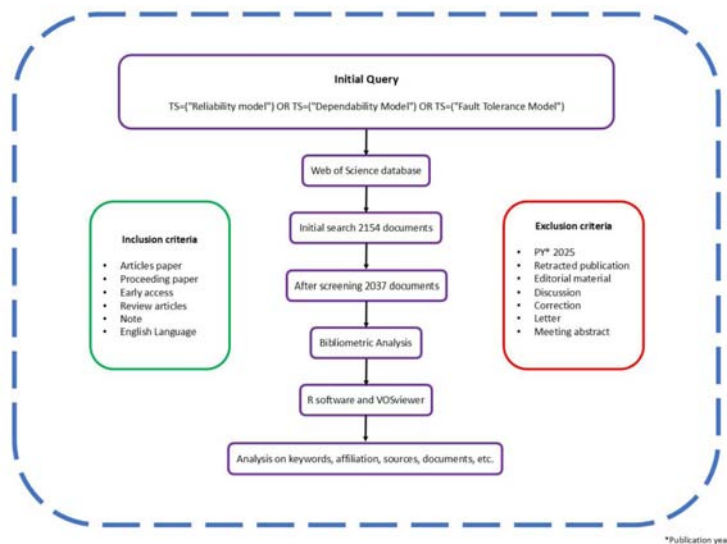


Figure 2

Flowchart illustrating the methodology applied

(TS=(\"Reliability model\")) AND ((DT==(\"ARTICLE\" OR \"PROCEEDINGS PAPER\" OR \"EARLY ACCESS\" OR \"REVIEW\" OR \"NOTE\") AND LA==(\"ENGLISH\")) NOT (PY==(\"2025\") OR DT==(\"RETRACTED PUBLICATION\")))

2.3 Bibliometric Analysis

The dataset comprised 2,037 records retrieved on 20 November 2024 and formed the basis of an in-depth bibliometric analysis generating quantitative and qualitative insights. R Studio with the Bibliometrix package supported science mapping, while VOSviewer (version 1.6.20) enabled network visualization [24], [25]. Data preparation involved removing duplicates and irrelevant records and standardizing author names, journal titles, and keywords to ensure consistency.

The analysis explored publication trends, citation impact, and collaboration patterns. Annual output and citation averages identified influential studies, while co-authorship analysis highlighted leading contributors and partnerships. Thematic mapping using author and algorithmic keywords revealed dominant and emerging topics. Journal influence was assessed using G-index and H-index indicators, with visual maps and graphs illustrating trends and relationships.

Although the adopted methodology provides a clear and reproducible framework for analysis, several limitations remain. The results may be influenced by the choice of search keywords, differences in citation behaviour among disciplines, difficulties in accurately identifying authors with similar names from different institutions, and the use of the Web of Science database as the sole data source, which may not include all relevant publications [26], [27]. Despite this, the study offers a view of reliability, dependability, and fault tolerance research.

3. Results and Discussions

We utilized R Studio's Bibliometrix package alongside VOSviewer to conduct an in-depth bibliometric analysis of 2,037 documents. This approach enabled us to identify key trends, visualize collaboration networks, and explore emerging themes within the research. The insights drawn from this analysis are systematically presented in the following sections:

3.1 Overview of the Reliability Model Research Dataset

3.1.1 Dataset characteristics

The bibliometric analysis of reliability model research summarized in Table 2 offers a detailed overview of key trends shaping the field. Covering publications from 1989 to 2024, the dataset includes 644 document sources drawn from journals, books, and other scholarly sources. A notable finding is the strong annual growth rate of 10.37%, reflecting a steady rise in research activity over time. The average document age of 9.56 years indicates that much of the work has been produced relatively recently, highlighting the field's growing relevance. This is reinforced by an average of 16.59 citations per document, suggesting a moderate yet meaningful academic impact. Collectively, these publications reference 47,146 sources, demonstrating extensive engagement with existing scholarship.

Table 2
Main information about data

Description	Results
Main information about data	
Timespan	1989 - 2024
Sources (Journals, Books, etc)	644
Documents	2037
Annual Growth Rate	10.37 %
Document Average Age	9.56
Average citations per doc	16.59
References	47146
Document contents	
Keywords Plus (ID)	2213
Author's Keywords (DE)	6022
Authors	
Authors	4926
Authors of single-authored docs	144
Authors collaboration	
single-authored docs	165
Co-authors per doc	3.51
International co-authorships %	19.64
Document types	
article	1886
article; early access	20
Article; proceedings paper	108
Note	3
Review	20
Documents and United Nations SDGs	
Goal 02 (Zero Hunger)	04
Goal 03 (Good Health and Well-Being)	80
Goal 04 (Quality Education)	01
Goal 05 (Gender Equality)	01
Goal 06 (Clean Water and Sanitation)	31
Goal 07 (Affordable and Clean Energy)	184
Goal 08 (Decent Work and Economic Growth)	01
Goal 09 (Industry Innovation and Infrastructure)	38
Goal 11 (Sustainable Cities and Communities)	207
Goal 12 (Responsible Consumption and Production)	83
Goal 13 (Climate Action)	34
Goal 14 (Life Below Water)	06
Goal 15 (Life on Land)	05
Goal 17 (Partnerships for the Goals)	04

3.1.2 Publication types

The content analysis reveals substantial thematic diversity, with 2,213 Keywords Plus entries and 6,022 author-defined keywords. In total, 4,926 authors contributed to the body of work, including 144 single-authored papers. Collaboration plays a significant role, as reflected by an average of 3.51 authors per document. Furthermore, international collaboration is evident, with 19.64% of the publications involving authors from multiple countries, emphasizing the global nature of reliability model research. Journal articles dominate the publication landscape, accounting for 1,886 documents, followed by conference proceedings, review papers, and a small number of early-access articles and notes.

Table 2 also illustrates how reliability model research aligns with the United Nations Sustainable Development Goals (SDGs). SDG 11 (Sustainable Cities and Communities) leads with 207 records, followed by SDG 7 (Affordable and Clean Energy) with 184 records, highlighting a strong emphasis on infrastructure resilience and energy reliability. SDGs related to responsible production and health are also well represented, while environmental goals receive moderate attention. In contrast, several social-focused SDGs remain underexplored, revealing clear opportunities for future interdisciplinary research.

3.2 *Growth and Evolution of Reliability Model Research*

3.2.1 Annual publication trends and dynamics over time

The bibliometric findings show that reliability model research has progressed markedly from 1989 to 2024. As illustrated in Figure 3, publication output remained moderate until 2007, followed by steady growth from 2008 and a sharp rise after 2010, peaking at 167 articles in 2022. Although output dipped slightly in 2023, it rebounded in 2024, confirming sustained interest. Figure 4 highlights citation trends, with steady growth until the mid-2000s and major peaks after 2005 and between 2015–2019, reflecting influential studies. The post-2020 decline likely reflects citation lag and pandemic effects.

3.2.2 Development phases of the field

Further enriching the analysis, Figure 5 presents a Sankey diagram that maps the complex collaborative networks in reliability model research. This visualization reveals robust interconnections among institutions, authors, and countries; notable research hubs such as Beihang University and Northeastern University emerge prominently, while influential authors like Zhang L, Pham H, Zio E, and Li JS are shown to actively engage in extensive collaborations. These – networks encompass a diverse group of nations, including China, the USA, Korea, Italy, and Iran, highlighting the truly global and interdisciplinary nature of the field. Collectively, these visualizations and trends not only reveal the expanding volume and impact of research in reliability models but also illustrate a vibrant, interconnected scholarly community poised for further innovation.

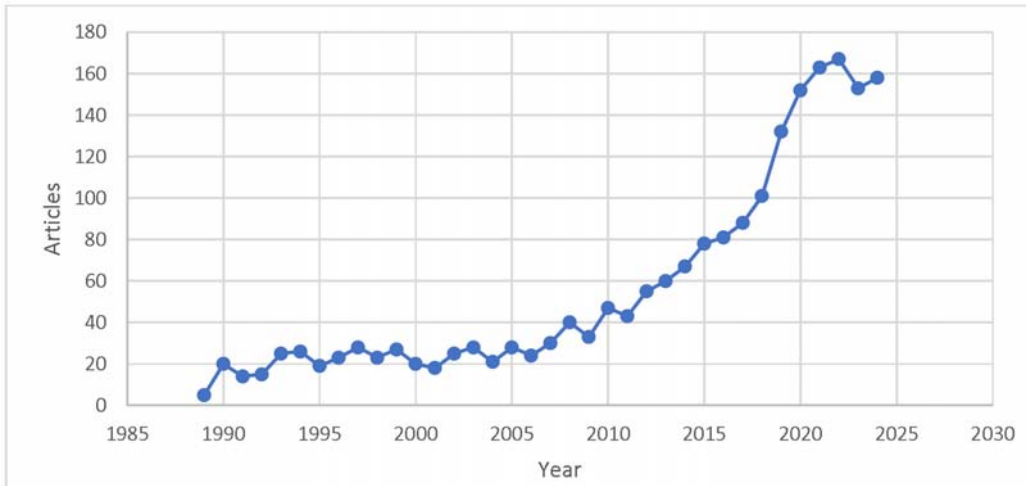


Figure 3
Yearly Progress in Scientific Contributions

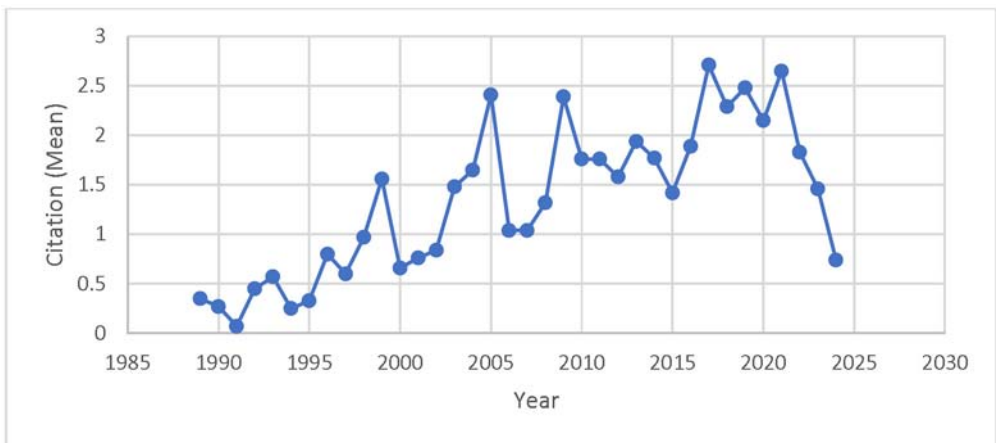


Figure 4
Yearly Citation Trends

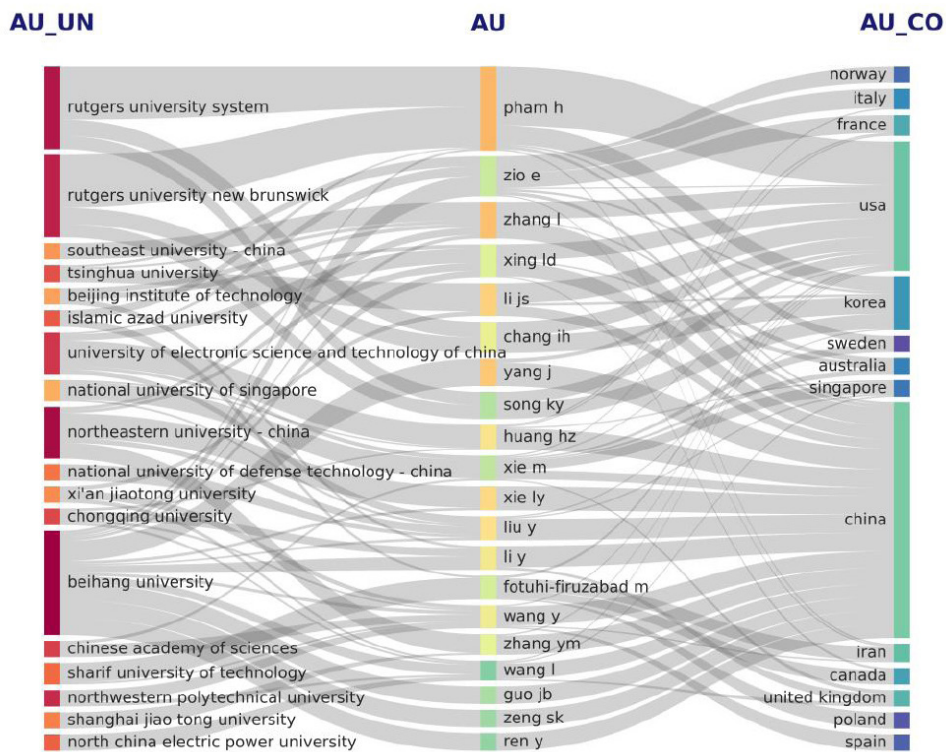


Figure 5

Three fields plot for Author (AU), Author University (AU_UN) and Author Country (AU_CO)

3.3 Geographical Distribution and International Collaboration Patterns

3.3.1 Leading countries/regions and global research contributions

At the international level, Figure 6 tracks publication growth across China, France, India, Iran, and the USA. China exhibits the most rapid expansion after 2007, surpassing the USA by 2016. The USA maintains consistent growth, while other countries show stable but moderate trends. Finally, Figure 7 distinguishes Single Country Publications (SCP) and Multiple Country Publications (MCP), revealing China's dominance in domestic output and the USA's balanced engagement in both national and international collaborations, underscoring varied global research strategies in reliability modelling.

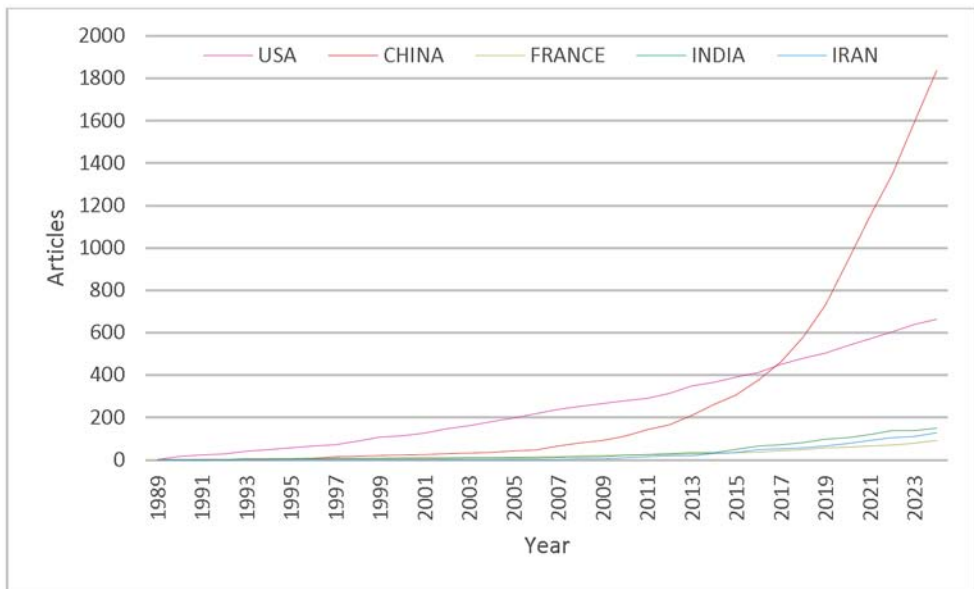


Figure 6
Country production over the time

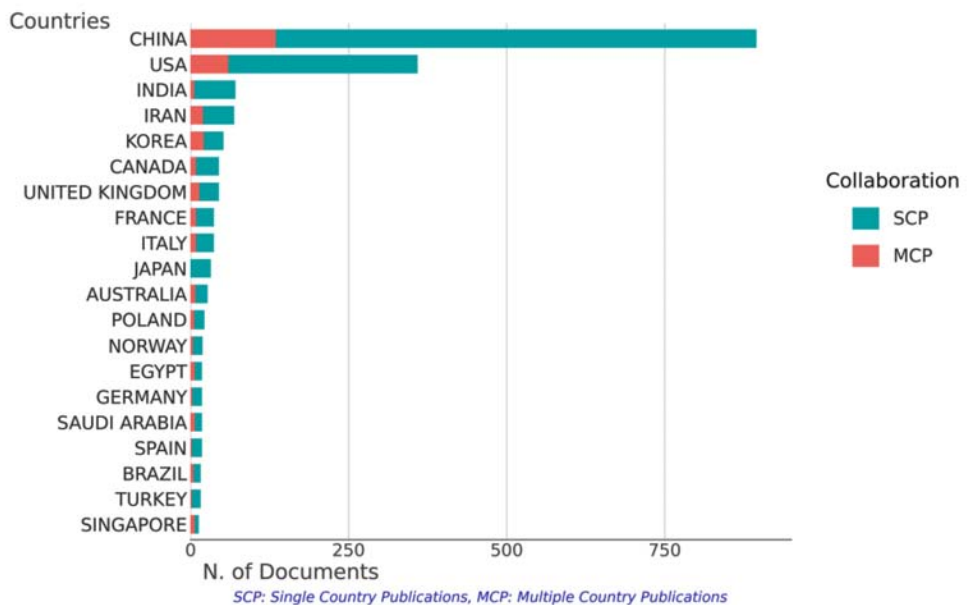


Figure 7
Corresponding author's countries

3.3.2 Country collaboration networks

Figures 8 and 9 together offer a clear picture of how countries collaborate in reliability model research, highlighting the international connections that support progress in this discipline. In Figure 8, each nation is represented as a node, where the intensity of the colour indicates the level of collaboration and the thickness of the connecting lines shows the strength of their partnerships.

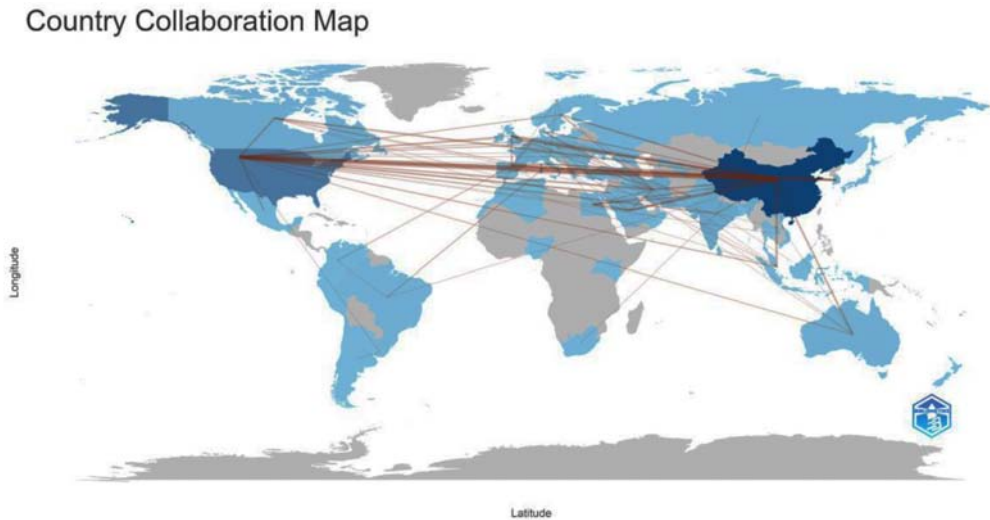


Figure 8
The collaboration among countries around the world

This map highlights major contributors like China and the USA as central hubs, deeply connected with various European nations, while also drawing attention to emerging players such as South Korea and Australia.

Similarly, Figure 9 employs a clustering approach to reveal international ties, with each country's node size reflecting its research output and collaborative strength. The color-coded clusters in this network illustrate groups of nations that often work together due to geographic proximity or shared research interests. Together, these figures illustrate that the global progress in reliability model research is primarily driven by a few key hubs that not only generate significant scholarly work but also foster cross-border partnerships.

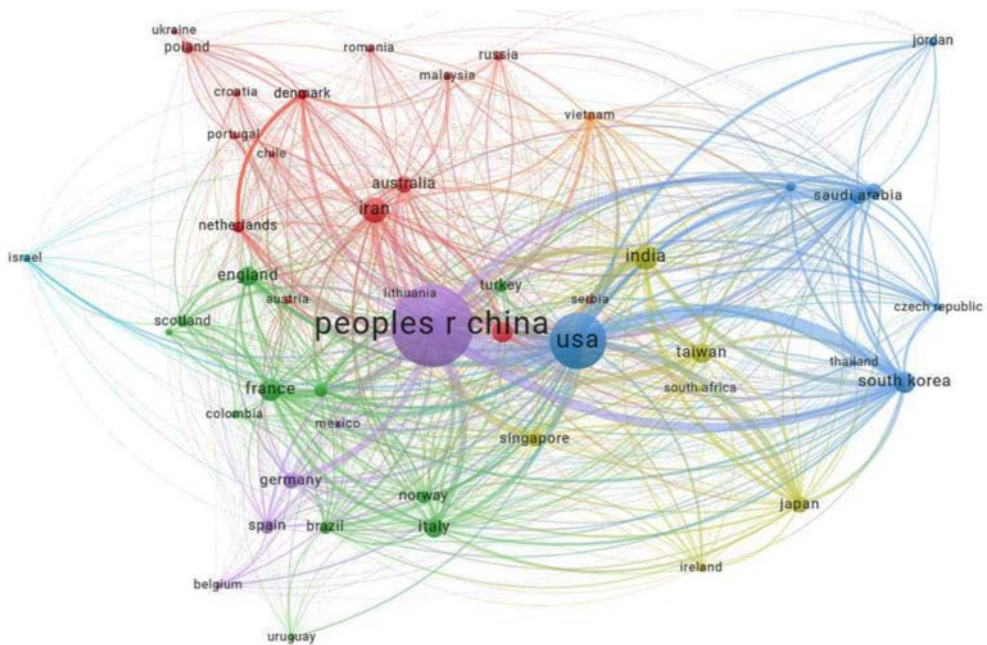


Figure 9
Global collaboration network in reliability model research
 (See for higher resolution: <https://tinyurl.com/2adseznl>)

3.4 Sources, Influential Documents, and Citation Structures

3.4.1 Most productive journals/sources

The publication landscape of reliability model research reveals clear trends over time, as summarized in Table 3, with Reliability Engineering & System Safety (RESS) emerging as the most influential journal. Since 1991, RESS has published 158 articles, achieved an h-index of 37 and a g-index of 54, and received 4,199 citations, highlighting its long-standing leadership. IEEE Transactions on Reliability also plays a key role, contributing 91 articles since 1990 and accumulating 2,820 citations. Other journals, such as Quality and Reliability Engineering International and Microelectronics Reliability, contribute steadily but with comparatively lower impact. Broader publication trends shown in Figure 10 indicate sustained growth for RESS and moderate expansion for IEEE Transactions on Reliability. Notably, IEEE Access shows rapid growth since 2017, reflecting its rising influence alongside established journals.

Table 3

Key Metrics and Rankings of leading zone 1 journals according to Bradford's Law (see Annexure I, Figure 19, for detail)

Source	Rank	Freq	Cum_Freq	h-index	g-index	m-index	TC	PY_start
RESS	1	158	158	37	54	1.06	4199	1991
IEEE Trans. Rel.	2	91	249	28	50	0.78	2820	1990
Qual. Reliab. Eng. Int.	3	64	313	14	20	0.44	575	1994
IEEE Access	4	49	362	13	22	1.45	616	2017
Microelectron. Reliab.	5	40	402	13	23	0.48	569	1999
Appl. Sci.	6	36	438	7	12	0.78	167	2017
Ekspl. Niezawodnosc	7	32	470	10	12	0.59	233	2009
J. Risk Reliab.	8	31	501	5	6	0.38	41	2013
Math. Probl. Eng.	9	29	530	7	13	0.27	211	2000
Comput. Ind. Eng.	10	22	552	10	20	0.28	411	1990
IEEE Trans. Pow Del.	11	22	574	14	22	0.41	926	1992
Commun. Stat.	12	17	591	7	16	0.21	273	1993
IEEE Trans. Pow Sys.	13	17	608	14	17	0.48	736	1997
Microelectron. Reliab.	14	17	625	13	23	0.48	569	1999
Int. J. Prod. Res.	15	16	641	11	16	0.46	351	2002
Mathematics	16	16	657	6	10	0.86	105	2019
Appl. Math. Model.	17	15	672	9	15	0.47	489	2007
Energies	18	14	686	5	7	0.62	68	2018

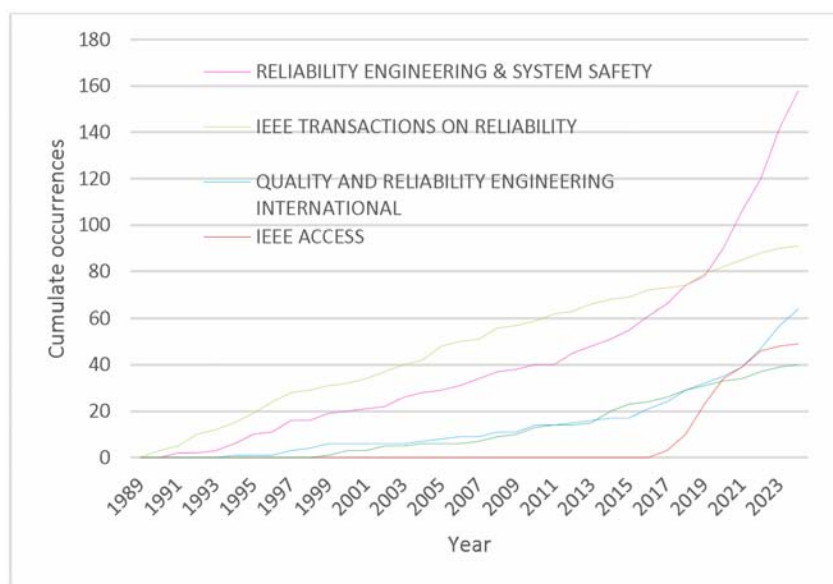


Figure 10

Cumulative publishing trends of key journals over time

Table 4

Top 20 Globally Cited Documents

(Metrics: TC - Total Citations, TCY - Citations per Year, N_TC - Normalized Citations)

Paper	DOI	TC	TCY	N_TC
PREACHER KJ, 2005, PSYCHOL METH	10.1037/1082-989X.10.2.178	538	25.62	10.61
STEWART MG, 1998, STRUCT SAF	10.1016/S0167-4730(97)00021-0	306	10.93	11.26
BIRMAN KP, 1999, ACM T COMP SYST	10.1145/312203.312207	305	11.30	7.25
PENG H, 2011, IIE TRANS	10.1080/0740817X.2010.491502	294	19.60	11.14
STEWART MG, 2009, STRUCT SAF	10.1016/j.strusafe.2007.12.001	235	13.82	5.80
LI WJ, 2005, IEEE T RELIAB	10.1109/TR.2005.847278	224	10.67	4.42
VÁZQUEZ M, 2008, PROG PHOTOVOL	10.1002/pip.825	220	12.23	9.26
MARTORELL S, 1999, RELIAB ENG SYST SAFE	10.1016/S0951-8320(98)00050-7	214	7.92	5.09
AMANULLA B, 2012, IEEE T POW DEL	10.1109/TPWRD.2011.2179950	205	14.64	9.26
NI YQ, 2010, J STRUCT ENG	10.1061/(ASCE)ST.1943-541X.0000250	191	11.94	6.80
GEBRAEEL N, 2009, IEEE T RELIAB	10.1109/TR.2008.2011659	189	11.12	4.66
LV ZH, 2021, IEEE T IND INFORM	10.1109/TII.2020.2994747	189	37.80	14.25
SONG SL, 2014, IEEE T RELIAB	10.1109/TR.2014.2299693	186	15.50	8.75
JIANG C, 2013, COMPUT METH APPL M	10.1016/j.cma.2012.10.020	184	14.15	7.30
SODHRO AH, 2019, IEEE T IND INFORM	10.1109/TII.2019.2902878	184	26.28	10.59
CAI BP, 2019, IEEE T IND INFORM	10.1109/TII.2018.2858281	173	24.71	9.96
PHAM H, 1999, IEEE T RELIAB	10.1109/24.784276	170	6.30	4.04
BALL MO, 1993, OPER RES	10.1287/opre.41.1.18	167	5.06	8.94
BASINGER M, 2010, J HYDROL	10.1016/j.jhydrol.2010.07.039	153	9.56	5.44
REUSSNER RH, 2003, J SYST SOFTWARE	10.1016/S0164-1212(02)00080-8	149	6.48	4.37

3.4.2 Highly cited publications

Table 4 highlights the twenty most influential publications in reliability model research based on total citations, citations per year, and normalized citation impact. The study by Preacher et al. achieved the highest citation count, demonstrating its sustained relevance across a wide range of research areas. Contributions by Stewart underscore the importance of safety and risk assessment in structural engineering, whereas the highly cited works of Birman and Peng reflect their significant influence on computational and industrial engineering applications. The distribution of highly cited publications also illustrates the changing focus of the field, with studies by Vázquez and Amanulla addressing topics related to photovoltaic systems and power delivery networks. More recent contributions from Lv and Sodhro indicate increasing research interest in industrial informatics, smart technologies, and IoT-based solutions, highlighting the emergence of these areas as important directions in contemporary reliability model research.

3.4.3 Citation and co-citation patterns

The RPYS analysis presented in Figure 11, spanning the period from 1763 to 2024, provides valuable insights into the historical development of reliability model research. The black curve represents the annual number of cited references and illustrates a steady growth in scholarly contributions, with a marked increase beginning in the 1960s and reaching its highest level around 2015. This pattern reflects the expanding research activity and growing academic attention devoted to the field. In contrast, the red curve depicts deviations from the five-year median, highlighting periods of exceptional research influence and intellectual advancement. The prominent peaks observed, particularly after 1990, indicate the publication of highly influential studies that significantly shaped subsequent research directions. The gradual decline in deviation values after 2015 suggests a transition toward a more mature and stable research domain, characterized by sustained growth rather than abrupt shifts in scholarly focus.

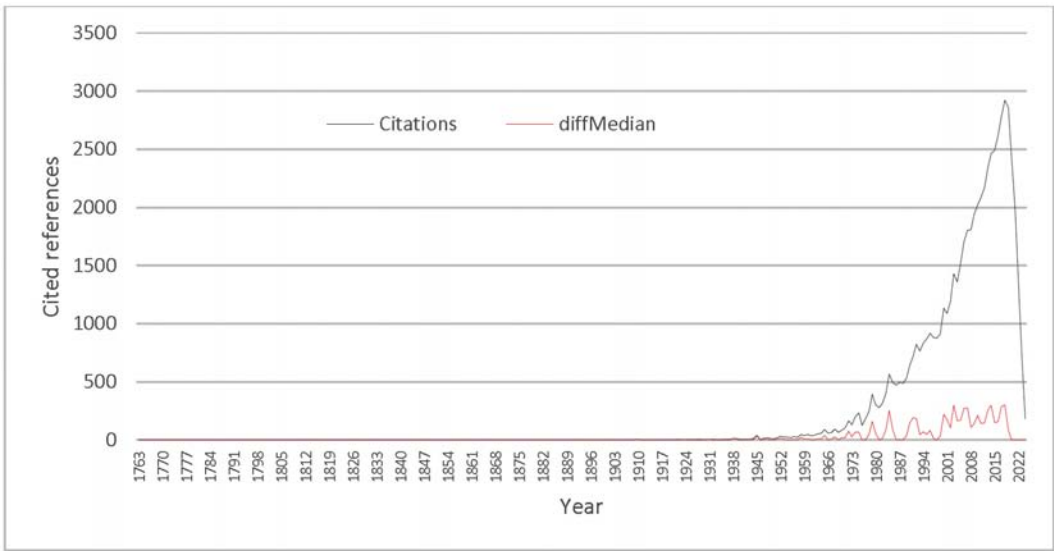


Figure 11
Reference Publication Year Spectroscopy (RPYS) of Reliability Model Research

3.4.4 Intellectual foundations of the field

Figure 12 displays a keyword co-occurrence network generated using VOSviewer, providing an overview of the thematic structure of reliability model research. The size of each node corresponds to the frequency of a keyword, while the connecting links represent relationships between topics based on their joint occurrence in the literature. The clustered arrangement of keywords highlights key research areas and emerging themes. Terms such as “model,” “reliability,” and “design” appear as central elements within the network,

reflecting their widespread relevance. The strong connections among clusters also indicate substantial interaction between research topics, particularly in areas related to optimization and allocation, which are closely associated with efforts to improve system effectiveness and resource utilization.

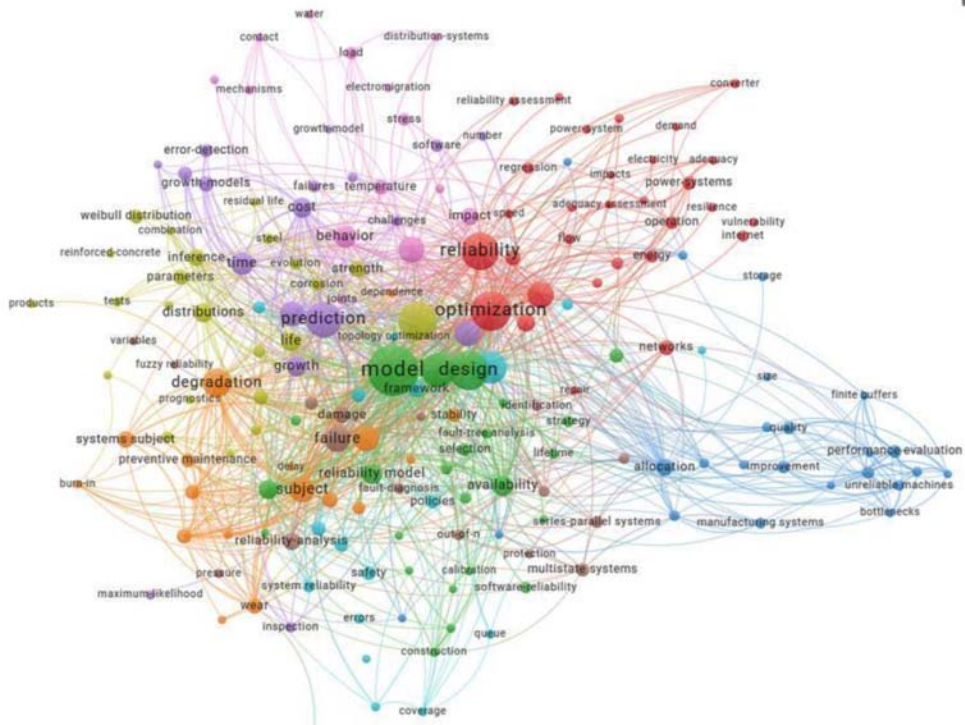


Figure 12
Co-occurrence network for keyword plus
(See for higher resolution: <https://tinyurl.com/2a5yzksd>)

3.5 Author Productivity, Collaboration Networks, and Research Impact

3.5.1 Most productive authors

Figure 13 and Table 5 together provide a comprehensive view of author contributions in reliability model research, capturing both publication volume and scholarly influence over time. Table 5 presents key performance indicators for the 20 most influential authors, including the Hirsch index (h-index) [28], Egghe's g-index [29], m-quotient (m-index), total citations (TC), number of publications (NP), and the year of first publication (PY_Start) [30]. Complementing this, Figure 13 visualizes annual publication activity from 1996 to 2024, where each dot represents an author's yearly output; larger dots indicate higher productivity, while darker shades reflect greater citation impact.

Table 5
Top 20 authors and their publication metrics
(TC - Total Citations, NP – Number of publications, PY_Start – Publication start year)

Author	h-index	g-index	m-index	TC	NP	PY_Start
PHAM H	21	37	0.70	1508	37	1996
ZHANG L	15	24	0.79	590	24	2007
LI JS	13	18	0.50	412	18	2000
FOTUHI-FIRUZABAD M	11	13	0.41	443	13	1999
XIE M	11	13	0.34	452	13	1994
HUANG HZ	10	16	0.59	328	16	2009
YANG J	10	19	0.41	486	19	2002
CHANG IH	9	13	1.00	171	14	2017
MEERKOV SM	9	9	0.35	297	9	2000
REN Y	9	12	0.64	269	12	2012
ZIO E	9	13	0.39	354	13	2003
CHE HY	8	11	0.89	237	11	2017
GUO JB	8	12	0.62	244	12	2013
LIU Y	8	15	0.57	232	16	2012
PENG R	8	11	0.62	298	11	2013
SONG KY	8	11	0.89	143	12	2017
SUN B	8	11	0.73	239	11	2015
XING LD	8	13	0.53	229	13	2011
ZENG SK	8	12	0.62	244	12	2013
ZHANG YM	8	14	0.67	204	14	2014

3.5.2 Author collaboration networks

The temporal patterns in Figure 13 reveal diverse trajectories of academic influence. For instance, PHAM H, whose work began in 1996, demonstrates consistent productivity across decades. Repeated appearances of large, dark markers indicate sustained output and strong citation performance, aligning with an h-index of 21, a g-index of 37, and 1,508 total citations. This reflects both long-term engagement and the presence of highly influential publications. In comparison, ZHANG L, active since 2007, exhibits periodic peaks in productivity and citation impact. Despite a shorter career span, a high m-index of 0.79 and an h-index of 15 indicate rapid recognition within the field. LI JS, whose contributions started in 2000, shows a steadier pattern of growth with a lower m-index of 0.50, suggesting a more gradual accumulation of scholarly influence.

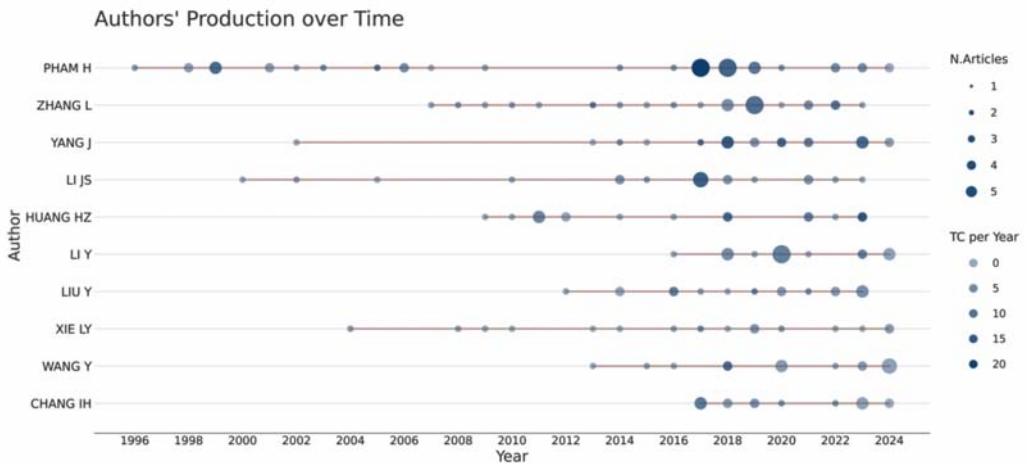


Figure 13
Authors' production over the time

3.5.3 Citation impact and influential scholars

Overall, these metrics demonstrate that research impact can emerge through different patterns of scholarly recognition. The m-index provides a useful perspective by considering the length of an academic career and assessing the rate at which an author's work gains visibility. CHANG IH achieves a notable m-index value of 1.00 despite having a relatively recent publication history beginning in 2017, reflecting a rapid rise in research influence. In comparison, the lower m-index values observed for XIE M and FOTUHI-FIRUZABAD M indicate a slower growth in citation impact, which may be associated with variations in research areas, publication timelines, or citation behaviour across disciplines. The comparison between h-index and g-index values further enhances the understanding of author impact, particularly in cases where the g-index is considerably higher. For PHAM H, the higher g-index compared with the h-index suggests that a limited number of highly influential publications have contributed significantly to the overall citation performance. These findings highlight that academic influence may result from either consistent research contributions over time or the strong impact of specific landmark studies.

Figure 14 illustrates the publication trends of leading institutions involved in reliability model research from 1989 to 2024. The overall pattern indicates a continuous increase in research output across all institutions, although the growth rate varies among them. Beihang University demonstrates a significant rise in publications after 2016, suggesting increased research activity supported by new initiatives, collaborations, or improved resources. Northeastern University and Northwestern Polytechnical University also show notable growth, reflecting their expanding contributions to the field. In comparison, the Egyptian Knowledge Bank and Rutgers-affiliated institutions exhibit a more gradual increase in research productivity over time. These variations highlight the influence of

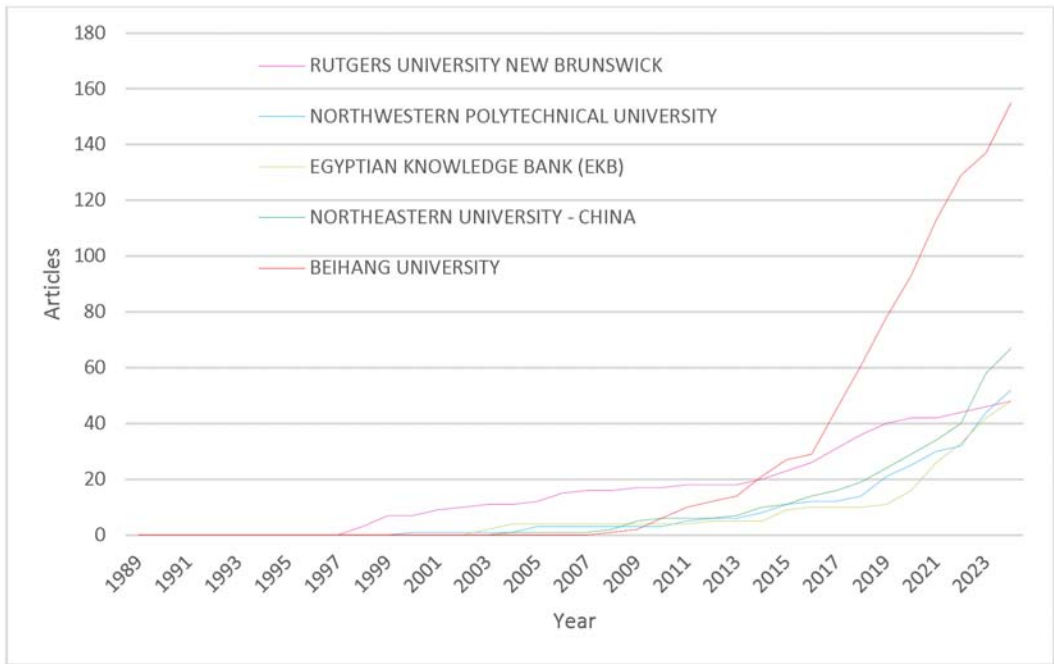


Figure 14
Affiliations’ production over the time

institutional factors, including funding availability, research strategies, collaboration networks, and infrastructure, in shaping publication performance within reliability model research.

3.6 Conceptual Structure and Thematic Evolution of Reliability Model Research

3.6.1 Keyword analysis

The research landscape of reliability modelling has undergone notable transformation, as illustrated through insights drawn from the tree map (Figure 15) and the timeline visualization (Figure 18). While the tree map highlights the frequency and relative importance of key terms within the literature, the timeline captures how research priorities have evolved over time. Together, these visualizations provide a comprehensive understanding of shifting scholarly focus and thematic development within the field.

As shown in Figure 15, the keyword “model” dominates the research space, appearing 189 times and representing approximately 10% of all recorded keywords. This prominence reflects the foundational role of modelling in reliability research. Other frequently occurring terms, including “design” (115 occurrences), “optimization” (114), and “systems” (106), indicate a strong emphasis on developing structured, efficient, and system-oriented solutions. Keywords such as “reliability” and “prediction,” each accounting for about 5% of occurrences, further highlight the growing importance of forecasting system behaviour

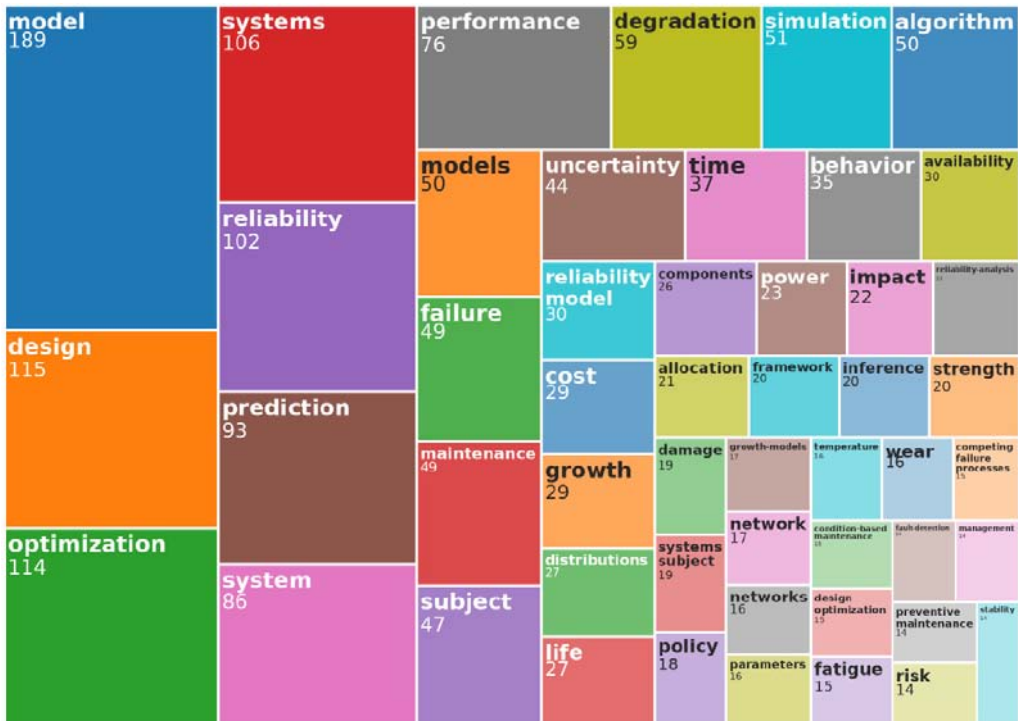


Figure 15

Tree map of Keywords in Reliability Model Research Highlighting Trends and Patterns in Document Dynamics

and ensuring dependable performance. Supporting terms like “performance,” “degradation,” “simulation,” and “algorithm” suggest methodological diversity, while more focused keywords such as “uncertainty,” “failure,” and “maintenance” point toward research addressing risk mitigation and long-term system sustainability.

3.6.2 Thematic maps

Figure 16 shows the thematic structure of reliability modelling research by categorizing important topics according to their development and relevance. Motor themes such as risk, methodology, framework, load, and temperature represent well-established research areas that support reliability evaluation and prediction. Niche themes, including performance assessment and production systems, are associated with focused industrial applications, while basic themes such as modelling, optimization, algorithms, and networks provide the foundation for reliability analysis approaches. Emerging areas involving power, energy, and network systems reflect the growing interest in sustainable and interconnected infrastructures, demonstrating the transition toward advanced, data-driven, and intelligent reliability solutions.

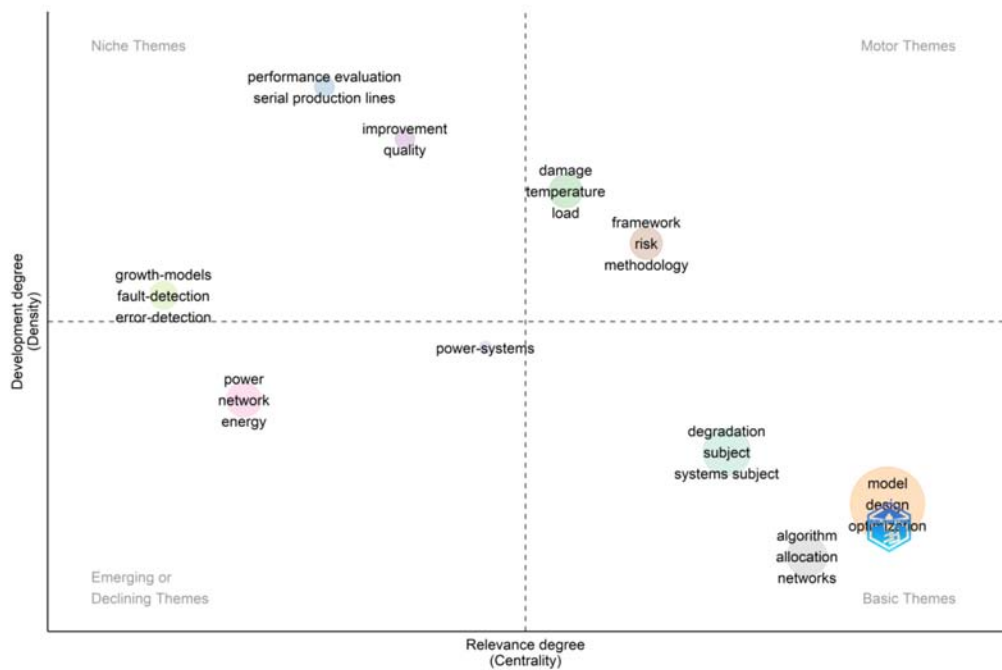


Figure 16
Thematic Map of key topics in reliability models

3.6.3 Thematic evolution

Figure 17 illustrates the long-term evolution of reliability model research from 1989 to 2024 using a Sankey diagram that visually tracks the flow and transformation of dominant research themes over time. By connecting color-coded keywords across successive periods, the figure highlights how scholarly attention has shifted in response to technological and methodological advancements.

During the early phase (1989–2007), research primarily concentrated on foundational reliability concepts such as error detection, software reliability, degradation, design, and methodological frameworks. This period established the core principles for evaluating reliability, particularly within software systems and structural applications. Between 2008 and 2015, the research scope broadened significantly. The keyword “model” emerged as a central theme, reflecting a growing emphasis on formalized and systematic reliability methodologies. At the same time, increased attention to maintenance, risk, probability, and uncertainty signalled a shift toward probabilistic analysis and risk-based decision-making. Interest in network reliability and performance assessment also grew, highlighting the rising complexity of interconnected systems.

From 2016 to 2019, research trends became more specialized and computationally driven. While modelling remained central, themes such as uncertainty analysis, failure

mechanisms, power systems, artificial neural networks, and fault-tree analysis gained prominence. This phase marked the integration of artificial intelligence and advanced analytics into reliability studies, indicating a methodological shift toward data-driven and network-based approaches.

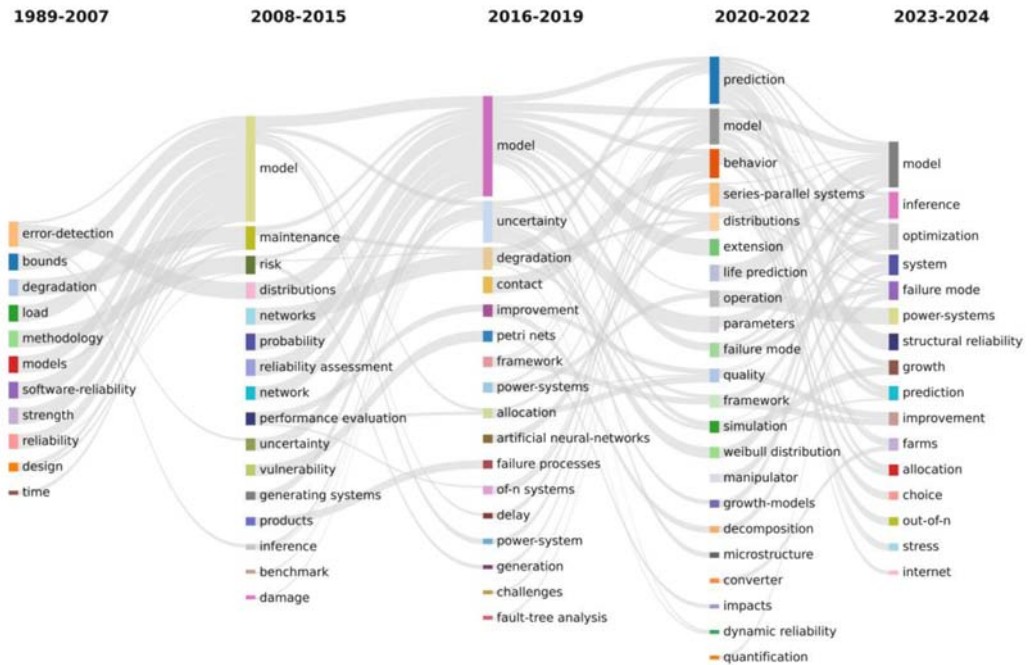


Figure 17

Sankey diagram illustrating the evolution of research themes across five distinct time periods

The period from 2020 to 2022 reflected a stronger focus on quantification and predictive reliability. Key topics included simulation, parameter estimation, decomposition techniques, life prediction, and failure mode analysis. The increased use of Weibull distributions and statistical reliability tools demonstrated the growing importance of real-time monitoring and predictive maintenance in modern systems.

In the most recent stage (2023–2024), research has advanced toward system-level optimization, structural reliability, and failure prevention. Greater emphasis on power systems, internet-enabled frameworks, and predictive models highlights the field's alignment with digital transformation, renewable energy integration, and large-scales infrastructure resilience.

3.6.4 Emerging research themes

The temporal evolution of these themes is captured in Figure 18. During the early 2000s, research attention was relatively fragmented, with sporadic mentions of niche topics such

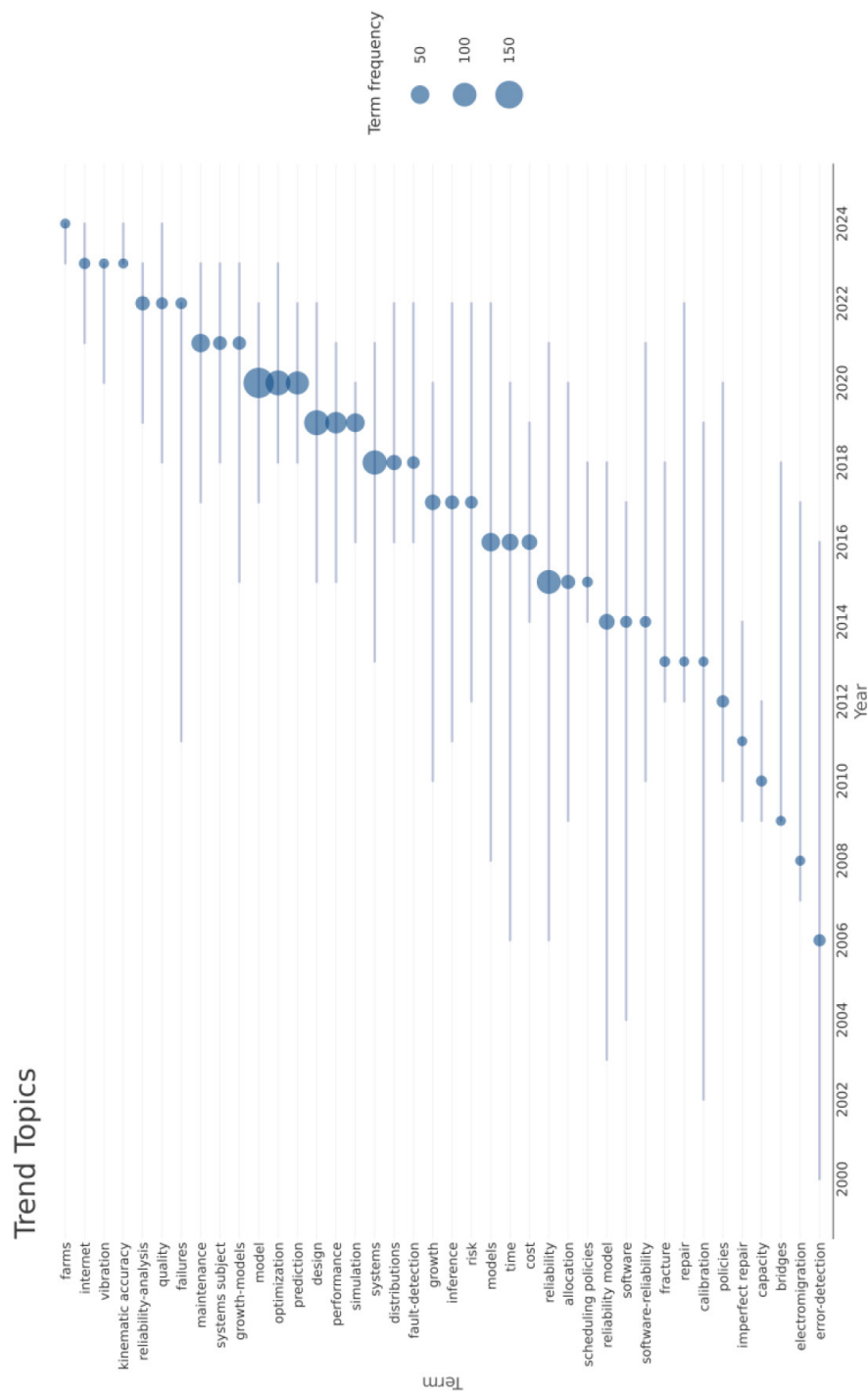


Figure 18
Trend topics in Reliability Model Research: A temporal analysis of key terms and their frequency

as “error detection,” “electromigration,” and “bridges.” Following 2010, the focus broadened to include themes like “software reliability,” “fault detection,” “risk,” and “models,” reflecting increasing interest in predictive maintenance and risk-based assessment. By the mid-2010s, advances in computational techniques drove the rise of keywords such as “optimization,” “simulation,” “prediction,” and “performance.” More recent years, particularly after 2018, show heightened attention to comprehensive system reliability, preventive maintenance, and failure prediction. Emerging terms such as “internet” signal the influence of digitalization and IoT technologies, while keywords like “kinematic accuracy” and “vibration” reveal growing interest in precision engineering and structural health monitoring.

4. Conclusion

The findings of this bibliometric study demonstrate the substantial growth and diversification of reliability modelling research over recent decades. Based on an analysis of 2,037 publications indexed in the Web of Science database, the field has maintained a steady annual growth rate of 10.37%, reaching its highest publication output in 2022. The average citation rate of 16.59 citations per document further indicates the continued relevance and influence of this research area. Although reliability modelling originated within traditional engineering disciplines, its applications now extend to areas such as artificial intelligence, software engineering, energy systems, and environmental management.

The thematic analyses presented in Figures 15, 17, and 18 reveal important changes in research focus. Earlier studies were largely concerned with hardware reliability and structural safety, whereas recent work increasingly emphasizes predictive modelling, data analysis, optimization techniques, and intelligent systems. The thematic evolution identified through the Sankey diagram reflects this progression and illustrates how the field has adapted to emerging technological developments and growing system complexity.

The results also highlight the importance of international research collaboration. While the United States and several European countries played a leading role in the early development of the field, China has become a major contributor since 2010, supported by the research output of institutions such as Beihang University and Northeastern University. The coexistence of highly influential researchers and newer contributors has supported both the continuity and advancement of knowledge. In addition, established journals continue to provide a strong publication platform, while the increasing presence of open-access outlets has broadened the visibility and accessibility of research findings.

The assessment of Sustainable Development Goal (SDG) alignment shows that reliability modelling research is most strongly associated with sustainable cities and communities (SDG 11) and affordable and clean energy (SDG 7). In contrast, topics related to inequality, institutional resilience, and peace receive limited attention, indicating areas that could benefit from greater interdisciplinary investigation.

Future developments in reliability modelling are likely to require a broader perspective that extends beyond technical performance. Issues such as cybersecurity, human behaviour, fairness, and equitable access to infrastructure are becoming increasingly relevant as reliability concerns intersect with social and digital systems. Addressing these dimensions may strengthen the contribution of reliability modelling to the development of resilient, sustainable, and inclusive systems.

Annexure – I

A. Details of abbreviation for sources used in Table 3

Abbreviation	Complete name of the Journal
RESS	RELIABILITY ENGINEERING & SYSTEM SAFETY
IEEE Trans. Rel.	IEEE TRANSACTIONS ON RELIABILITY
Qual. Reliab. Eng. Int.	QUALITY AND RELIABILITY ENGINEERING INTERNATIONAL
IEEE Access	IEEE ACCESS
Microelectron. Reliab.	MICROELECTRONICS RELIABILITY
Appl. Sci.	APPLIED SCIENCES-BASEL
Ekspl. Niezawodnosc	EKSPLOATACJA I NIEZAWODNOSC-MAINTENANCE AND RELIABILITY
J. Risk Reliab.	PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART O-JOURNAL OF RISK AND RELIABILITY
Math. Probl. Eng.	MATHEMATICAL PROBLEMS IN ENGINEERING
Comput. Ind. Eng.	COMPUTERS & INDUSTRIAL ENGINEERING
IEEE Trans. Pow Del.	IEEE TRANSACTIONS ON POWER DELIVERY
Commun. Stat.	COMMUNICATIONS IN STATISTICS-THEORY AND METHODS
IEEE Trans. Pow Sys.	IEEE TRANSACTIONS ON POWER SYSTEMS
Microelectron. Reliab.	MICROELECTRONICS AND RELIABILITY
Int. J. Prod. Res.	INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH
Mathematics	MATHEMATICS
Appl. Math. Model.	APPLIED MATHEMATICAL MODELLING
Energies	ENERGIES

B. Core Sources by Bradford's Law

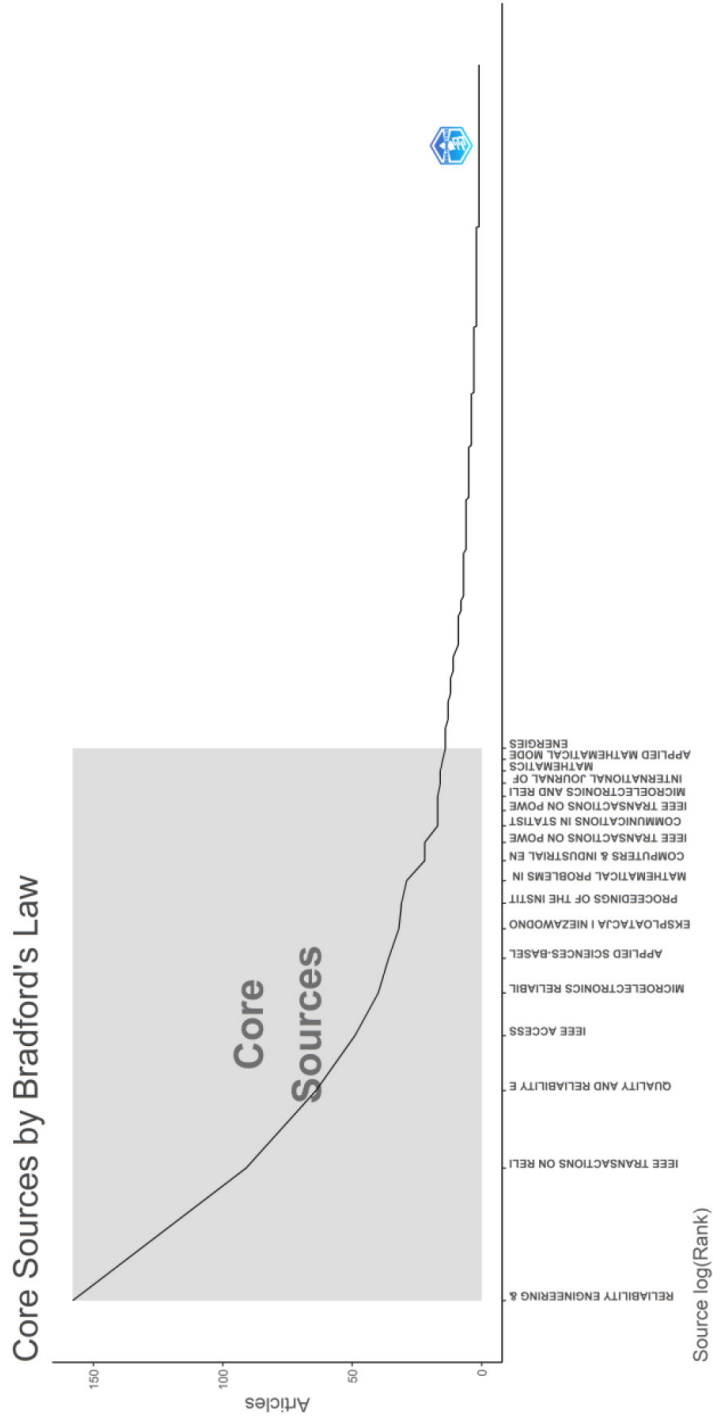


Figure 19
Core sources by Bradford's Law - Zone 1

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