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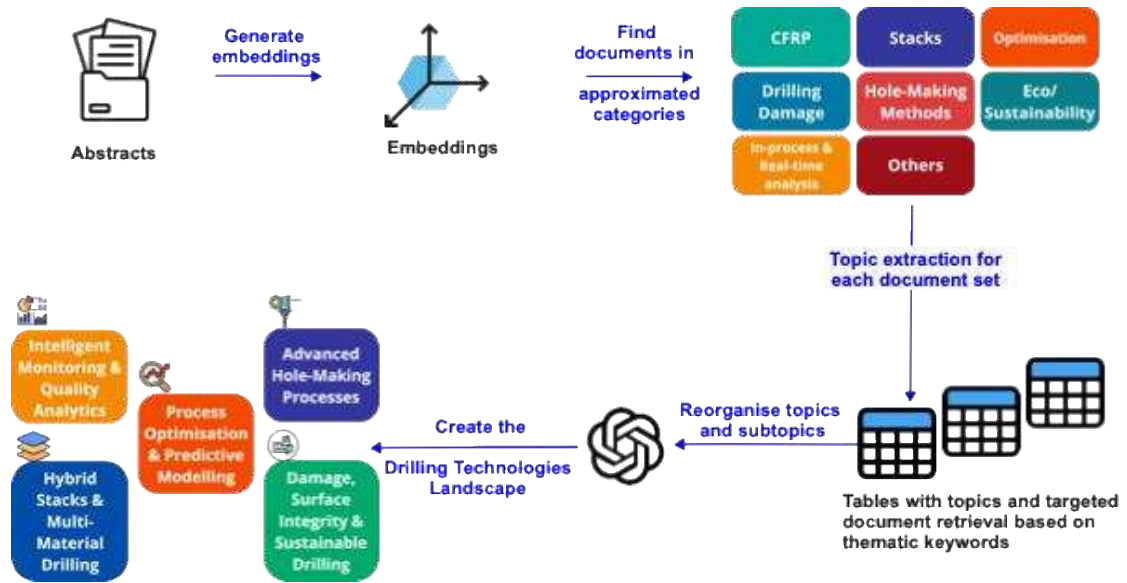
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Graphical abstract



Mapping Technological Advances in Drilling for Aircraft Manufacturing: A Hybrid Bibliometric and Expert-Guided Review

Yuri Mejia^{1§}, Windo Hutabarat¹, Ashutosh Tiwari¹, Alvaro Leal², Robert Whiffen², Phillip Edwards²

¹ School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, Sheffield S1 4DT, UK

² Airbus Operations Limited, Chester Road, Broughton, Chester, CH4 0DR, UK

§Corresponding author

Abstract

Drilling is a pivotal operation in aircraft manufacturing, directly affecting assembly precision, fastening reliability, and structural integrity. Despite its significance, previous reviews have largely concentrated on isolated machining challenges, specific material stacks, or narrow process variables, often overlooking broader technological evolution across the aerospace drilling domain. This study addresses this gap by systematically mapping recent advances in drilling technologies for aircraft manufacturing through a hybrid review methodology that integrates bibliometric analysis, semantic topic modelling, and expert-guided taxonomy refinement. A comprehensive literature corpus was constructed and analysed to identify research theme clusters, emerging trends, and key contributors. The resulting five-theme taxonomy captures the field through: intelligent monitoring and quality analytics; hybrid stacks and multi-material drilling; process optimisation and predictive modelling; advanced hole-making processes; and damage, surface integrity, and sustainable drilling. The review reveals a clear transition from conventional parameter optimisation towards digitally enabled drilling systems characterised by in-process sensing, adaptive control, machine-learning-assisted prediction, and autonomous quality assurance. In parallel, growing research attention is directed towards hybrid material stacks, non-conventional hole-making techniques, and sustainable machining strategies to improve process robustness and manufacturing efficiency. Beyond synthesising current technological directions, this work demonstrates a replicable and scalable methodology for evidence-based research mapping in high-value manufacturing, providing a structured foundation for future aerospace drilling research and industrial implementation.

Key words: Aircraft drilling, Aerospace manufacturing, Intelligent process monitoring, Bibliometric topic mapping

1 Introduction

The manufacture of modern aircraft structures is fundamentally dependent on mechanical fastening, with drilling representing one of the most critical operations for ensuring structural integrity, dimensional precision, and assembly reliability. Throughout the aerospace sector, including commercial, business, government, and space applications, contemporary aircraft feature an exceptionally large number of drilled holes; for example, a typical single-aisle aluminium commercial aircraft contains over three million holes [1]. These are commonly produced in stacked assemblies comprising dissimilar materials such as carbon fibre-reinforced polymers (CFRP), titanium, and aluminium alloys, frequently using single-shot drilling strategies to maintain positional accuracy and reduce assembly errors [2]. Because bolted joints remain the dominant joining solution in aerospace structures due to their high load-bearing capability and reparability, drilling quality directly influences joint performance, fatigue resistance, and long-term structural reliability [3].

Driven by persistent challenges such as delamination, burr formation, thermal damage, rapid tool wear, and poor hole dimensional accuracy, aerospace drilling has evolved beyond conventional twist drilling towards more advanced hole-making strategies. These include helical milling, orbital drilling, vibration-assisted drilling, robotic drilling platforms, cryogenic and minimum quantity lubrication (MQL) assistance, and increasingly sensor-rich intelligent drilling systems capable of real-time monitoring and adaptive optimisation [4]. As a result, drilling research in aircraft manufacturing now spans multiple interacting dimensions, including material-specific damage mechanisms, process assistance technologies, tool design, robotic integration, sensing architectures, data-driven optimisation, and digital manufacturing frameworks.

Several recent review studies have significantly advanced understanding within specific subdomains of this broader landscape. For example, Zhu et al. [5], and Rampal et al. [6] provide detailed syntheses of CFRP drilling optimisation, particularly focusing on delamination control, parameter selection, and tool geometry. Franz et al. [7] extend this perspective to FRP/Al stacks and fibre-metal laminates, systematically reviewing one-shot drilling performance metrics and optimisation strategies, including vibration-assisted drilling, orbital drilling, cryogenic cooling, and MQL. Similarly, recent reviews on CFRP/Ti stack drilling consolidate findings on process indicators such as thrust force, temperature, chip morphology, tool wear, and post-drilling quality metrics, while highlighting limitations in coating tribology assessment, cylindricity evaluation, and the industrial maturity of advanced drilling techniques [8]. Jiao et al. [9] further examine damage mechanisms at CFRP/Ti interfaces, particularly at the stack transition region.

More recently, the literature has expanded towards intelligent and data-driven drilling paradigms. Panico and Boccarusso [10] present a comprehensive narrative review of smart drilling systems, structuring the field around sensing modalities, tool-condition monitoring, process optimisation, and predictive quality modelling. Their review provides important guidance on integrating sensor signals with AI architectures while identifying key research bottlenecks related to dataset scarcity, model transferability, and interpretability. In parallel, recent data-driven CFRP machining reviews position machine learning as a stand-alone optimisation layer for machining performance prediction, while similarly emphasising the persistent limitations of data scarcity and weak model explainability [11].

Although these studies provide substantial technical depth, they remain predominantly narrative and expert-structured, with thematic organisation largely determined by manually predefined

subsections and author-defined taxonomies. This review style is highly effective for focused technical surveys but offers limited capability for systematically uncovering latent semantic relationships across adjacent drilling domains, particularly where terminology overlaps with broader machining, composite manufacturing, structural assembly, robotics, and digital manufacturing literature. This limitation becomes particularly significant in the context of broader manufacturing bibliometric studies, which often rely primarily on co-word statistics, citation networks, or unsupervised clustering. While these approaches are effective for detecting macro-level trends, they frequently lack the semantic resolution needed to distinguish closely related but technologically distinct aerospace drilling concepts [12]. In practice, this can lead to fragmentation of interconnected themes or, conversely, the merging of technically different process innovations into overly broad clusters. Consequently, the technological evolution of drilling in aircraft manufacturing remains insufficiently represented as a coherent, cross-disciplinary, and methodologically reproducible research landscape.

To address this gap, the present study proposes a hybrid semantic evidence-building review methodology that integrates bibliometric mapping, exploratory topic modelling, semantic embedding-based retrieval, expert-guided thematic consolidation, subset-level topic modelling, and AI-assisted synthesis. The fundamental novelty lies not merely in combining these analytical techniques, but in establishing a systematic workflow in which semantic evidence actively supports the construction, refinement, and validation of the review taxonomy itself. Rather than imposing fixed review categories a priori, the methodology enables higher-level technological domains to emerge iteratively through interaction between machine-discovered semantic structures and aerospace manufacturing expertise. A targeted corpus was assembled from leading scientific databases using a focused search strategy designed to capture drilling technologies relevant to aircraft manufacturing while excluding unrelated industrial sectors.

Exploratory corpus analysis was initially performed using the PyBibX Python library [13], enabling the detection of recurrent author keywords and indexed concepts directly grounded in the retrieved literature. This point is methodologically important because the semantic evidence used for theme development is based on the real author keywords and indexed concepts present in the source documents, rather than externally imposed descriptors. The preliminary machine-generated structures were subsequently refined through expert-guided thematic classification, allowing semantically overlapping manufacturing concepts to be consolidated into aerospace-relevant technology trajectories. For deeper analysis, the emerging cluster intelligent monitoring & quality analytics was further investigated through targeted retrieval from the Dimensions database [14] and concept co-occurrence mapping to identify foundational publications, semantic bridges, and evolving research trajectories.

2 Selection criteria

To provide a comprehensive and reproducible overview of the aerospace drilling research landscape, the literature retrieval stage was conducted using two major multidisciplinary scientific databases: Web of Science [15], and Scopus [16]. These databases were selected because of their extensive coverage of high-quality peer-reviewed engineering, manufacturing, and materials science literature. The search strategy was intentionally designed as a broad discovery-stage query to maximise thematic coverage. Rather than restricting the retrieval to explicitly digital or in-process

terminology at this stage, the query was formulated to capture the wider aerospace drilling ecosystem, including hybrid material stacks, advanced hole-making methods, and process-quality studies. The following Boolean query was used in Scopus:

```
( TITLE-ABS-KEY (
("aerospace" OR "aircraft" OR "aviation" OR
"aerostructure*" OR "airframe*" OR "fuselage" OR
"CFRP/Ti" OR "CFRP-Ti" OR "hybrid stack*" OR
"stack drilling" OR "one-shot" ) )
AND TITLE-ABS-KEY (
("drill*" OR "hole-making" OR "hole quality" OR
"laser drilling" OR "abrasive water jet" OR
"mechanical drilling" OR "orbital drilling" OR
"helical milling" ) )
AND LANGUAGE ( English )
AND NOT TITLE-ABS-KEY ( ( "oil" OR "gas" ) )
AND ( LIMIT-TO ( PUBSTAGE , "final" ) )
AND ( LIMIT-TO ( DOCTYPE , "ar" ) )
OR LIMIT-TO ( DOCTYPE , "re" ) )
```

An equivalent Boolean expression, adapted to the Web of Science topic-field syntax, was used to ensure consistency between the databases. The Scopus search returned 2334 documents, while the equivalent Web of Science query retrieved 1715 documents. The inclusion criteria for this retrieval stage were defined as follows:

- **Topical relevance:** studies addressing aerospace drilling, hybrid composite--metal stacks, or related hole-making processes. Also, publications covering conventional or advanced drilling methods, including mechanical, laser, abrasive water jet, orbital drilling, and helical milling.
- **Exclusion of unrelated fields:** Studies focusing on drilling within the oil and gas sector were omitted to maintain an emphasis on aerospace and advanced manufacturing contexts.
- **Document type:** Only journal articles and review papers were considered.
- **Language:** The literature search was restricted to publications written in English.
- **Time frame:** All publications dating from 1900 to 2026 (March) were included, thereby capturing both seminal and contemporary contributions.

3 Exploratory Data Analysis

The exploratory data analysis begins with an overview of the document collection, as summarised in Table I. This table presents key statistics derived from merging bibliometric records obtained from both Web of Science and Scopus, using the collection-joining capabilities of the PyBibX Python library [13]. The analysis is then further developed through a series of visualisations, including the distribution of concepts identified via combined bigram and trigram phrase extraction, the evolution of keywords over the period from 2017 to 2026, and a Sankey diagram illustrating the flow of research outputs from the top eight publishing countries to their leading institutions. Each institution

is additionally linked to individual researchers, thereby highlighting specific contributions within the wider context of academic collaboration.

Table 1 provides summary statistics for the document collection, which spans the period from 1932 to 2026. The dataset comprises publications from 785 journals, representing 83 countries and 2648 institutions. On average, there are 1.37 documents per author, 4.18 documents per institution, and 3.3 documents per source. Across the collection, there are 8054 authors and 6235 distinct author keywords. Of the 2597 documents, 191 are single-authored, while 2406 are multi-authored.

Table I. Merged metadata report (WoS and Scopus).

Information	Results
Timespan	1977-2026
Total Number of Countries	58
Total Number of Institutions	770
Total Number of Sources	209
Total Number of Documents	552
--Article	520
--Review	32
Average Documents per Author	1.19
Average Documents per Institution	3.11
Average Documents per Source	2.64
Average Documents per Year	17.25
Total Number of Authors	2012
Total Number of Authors Keywords	1740
Total Number of Authors Keywords Plus	3633
Total Single-Authored Documents	15
Total Multi-Authored Documents	537
Average Collaboration Index	4.34
Max H-Index	9
Total Number of Citations	13299
Average Citations per Author	6.61
Average Citations per Institution	17.27
Average Citations per Document	24.09
Average Citations per Source	63.63

3.1 Distribution of concepts

This subsection provides an initial overview of the key concepts present within the document collection. The distribution of concepts was examined using n -gram extraction techniques. In natural language processing, an n -gram refers to a contiguous sequence of n items, typically words in a text; for example, a 2-gram (bigram) comprises two adjacent words, while a 3-gram (trigram) comprises

three. This method facilitates the identification of recurring phrases and contextual patterns that may be missed by single-word analysis. The *get_top_ngrams()* function was applied to the keywords from authors with *n* set to 2 and 3, following the removal of a comprehensive list of generic or non-informative terms. Figure 1 shows the resulting bigrams and trigrams from the document keywords.

To estimate the overall distribution of key concepts within the corpus, a manual consolidation process was performed after the extraction of bigrams and trigrams. Conceptually equivalent expressions and closely related keyword variants appearing across both lists were merged into unified thematic categories using British English conventions. For example, terms such as “carbon fiber”, “carbon fiber reinforced”, “carbon fibre reinforced”, “fiber reinforced”, and “fiber reinforced polymer” were consolidated under the category “carbon fibre-reinforced polymer (CFRP)”. Likewise, “water jet”, “abrasive water”, “abrasive water jet”, “water jet cutting”, and “abrasive waterjet” were grouped under “abrasive water jet machining”. Similarly, “CFRP/Ti”, “CFRP-Ti stacks”, and “Ti stacks” were unified as “CFRP-Ti stacks”.

This manual grouping enabled a more general estimation of each concept's prevalence, as visualised in the pie chart in Figure 2, and provided a clearer representation of the dominant and emerging topics within the dataset. Percentages were calculated from the frequencies of the unified keyword categories after consolidation. The results indicate that carbon fibre-reinforced polymer (CFRP) remains the most dominant topic, accounting for approximately 22.2 % of all unified keyword occurrences, which highlights the central role of composite materials in aerospace drilling research. Abrasive water jet machining follows closely at 22.0 %, reflecting strong and growing interest in non-conventional machining approaches for difficult-to-machine aerospace materials. Surface roughness, surface integrity, and surface quality collectively represent 12.5 %, demonstrating the continued importance of output quality and functional performance. Research on CFRP--Ti stacks accounts for 10.1 %, further emphasising the industrial relevance of hybrid material stacks in aircraft assembly. Thrust and cutting force-related studies contribute 9 %, confirming the strong focus on process mechanics and machinability. Additional recurring themes include tool wear (6.4 %), vibration-assisted machining (5.1 %), titanium alloys (4.6 %), and finite element modelling (3.1 %), while residual stress and heat-affected phenomena appear as more specialised yet still relevant topics. The reported categories account for 86.2 % of the total unified keyword occurrences, while the remaining 13.8 % corresponds to lower-frequency specialised or emerging themes that were retained outside the major thematic groups to preserve figure readability and avoid over-fragmentation.

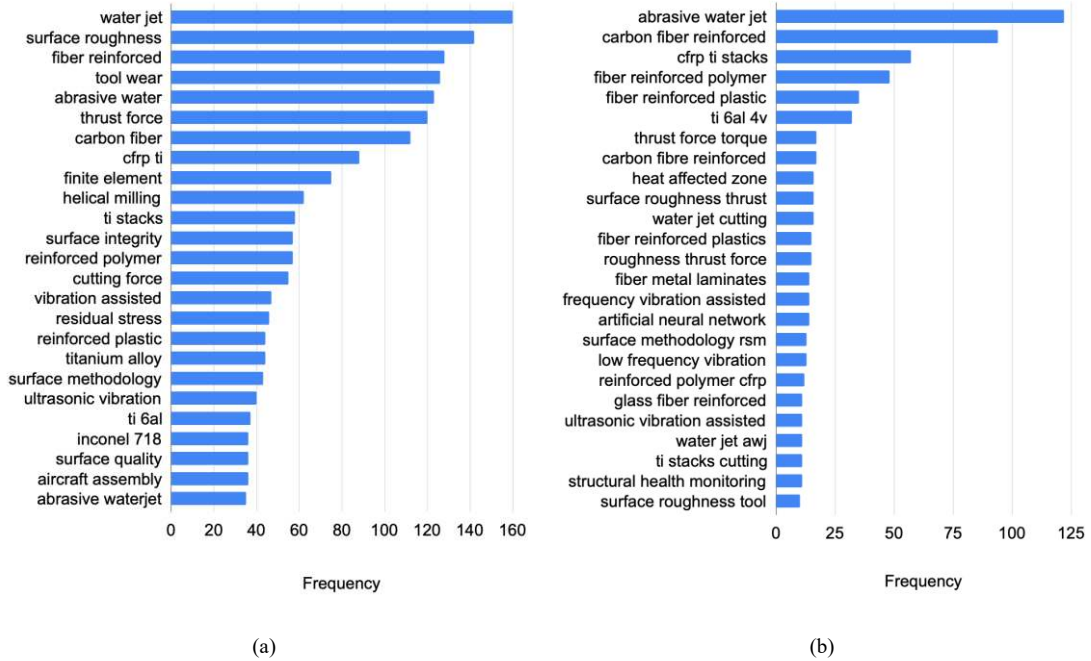


Fig.1 List of (a) bigrams and (b) trigrams from the authors' keywords of the document collection.

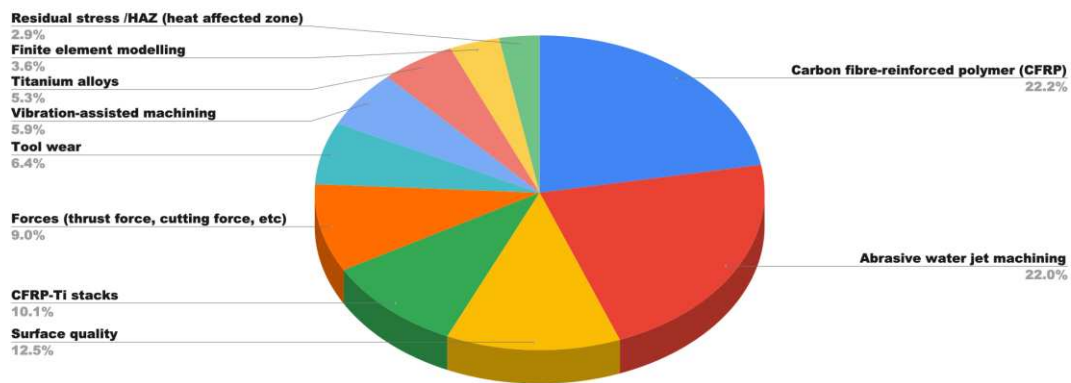
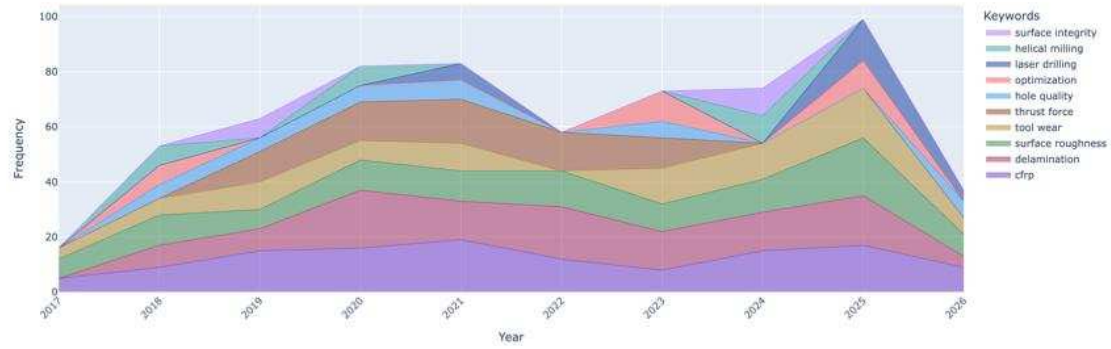


Fig. 2 Distribution of concepts combined from the bigrams and trigrams information. Carbon fibre-reinforced polymer dominates at 22.2 %, followed by Abrasive water jet machining at 22.0 %. Other notable topics include Surface quality (12.5 %), CFRP-Ti stacks (10.1 %), and Forces (thrust force, cutting force, etc) (9.0 %). Other important topics are Tool Wear, Vibration-assisted machining, Titanium alloys, Finite element modelling and Residual stress/HAZ, representing around 24 %.

Figure 3 illustrates the temporal evolution of research themes in aerospace drilling from 2017 to 2026, revealing a clear progression in the prominence of author-supplied keywords. In the initial phase (2017-2018), the literature was primarily oriented towards surface generation and quality assessment, with roughness, surface roughness, and tool wear emerging as dominant concerns. At the same time, early attention to CFRP, aircraft assembly, and abrasive machining indicates the growing relevance of composite structures and assembly-related hole-making challenges in aerospace applications. By 2018, topics such as delamination, helical milling, optimisation, and abrasive water jet machining became increasingly visible, reflecting an early emphasis on damage mitigation and alternative hole-making strategies.



(a)



(b)

Fig. 3 Temporal evolution of key research topics in advanced drilling for aerospace manufacturing from 2017 to 2026. (a) Stacked area chart showing the annual frequency trends of selected high-impact author keywords, capturing the sustained prominence of CFRP, delamination, tool wear, thrust force, and surface roughness, alongside the growing visibility of non-conventional drilling processes such as laser drilling, helical milling, and abrasive water jet machining. Collectively, both subfigures reveal the field's evolution from material- and defect-oriented studies towards intelligent, multi-process, and system-level optimisation frameworks. (b) Keyword block chart illustrating the relative frequency and yearly prominence of dominant research themes, highlighting the progression from early studies focused on surface roughness, CFRP, and assembly-related drilling challenges towards broader themes including delamination control, robotic drilling, additive manufacturing, 3D printing, laser drilling, and surface integrity. The visualisation emphasises the increasing diversification of the field from conventional defect and quality assessment towards integrated, automated, and digitally enabled aerospace manufacturing systems.

A marked consolidation around composite drilling is observed during 2019-2021, where CFRP becomes the most persistent research theme. This period is characterised by strong growth in studies focused on process-induced damage and machinability indicators, particularly delamination, thrust force, tool wear, surface roughness, and hole quality. The rise of surface integrity and hole diameter in 2019-2020 further suggests a shift towards precision-driven performance evaluation. By 2021, the emergence of laser drilling and Inconel 718 highlights an expansion beyond polymer composites towards non-conventional drilling methods and difficult-to-machine aerospace alloys, signalling broader material and process diversification.

Between 2022 and 2023, the field enters a phase of methodological diversification and system-level process analysis. While established topics such as delamination, thrust force, surface roughness, and tool wear remain central, new keywords, including ANOVA, robotic drilling, aircraft assembly, and CFRP/Ti stacks, indicate a stronger orientation towards statistical modelling, automated drilling platforms, and multi-material aerospace structures. The persistence of optimisation during this stage further reflects sustained interest in parameter tuning and predictive performance modelling. Overall, this period marks the transition from material-centric studies towards integrated drilling system optimisation.

In the most recent period (2024-2026), the thematic landscape broadens towards intelligent, hybrid, and digitally enabled manufacturing systems. Although CFRP, delamination, tool wear, and surface roughness remain dominant, the growing prominence of surface integrity, additive manufacturing, 3D printing, and renewed interest in helical milling suggests stronger integration between drilling research and advanced production ecosystems. The pronounced rise of laser drilling, abrasive water jet, cutting force, and optimisation in 2025 further reflects increasing attention to high-precision, non-conventional, and data-assisted machining routes. By 2026, the keyword distribution suggests a partial stabilisation of the field around core quality metrics, particularly CFRP, surface roughness, hole quality, and tool wear, indicating the sustained centrality of defect control and surface performance in next-generation aerospace drilling research.

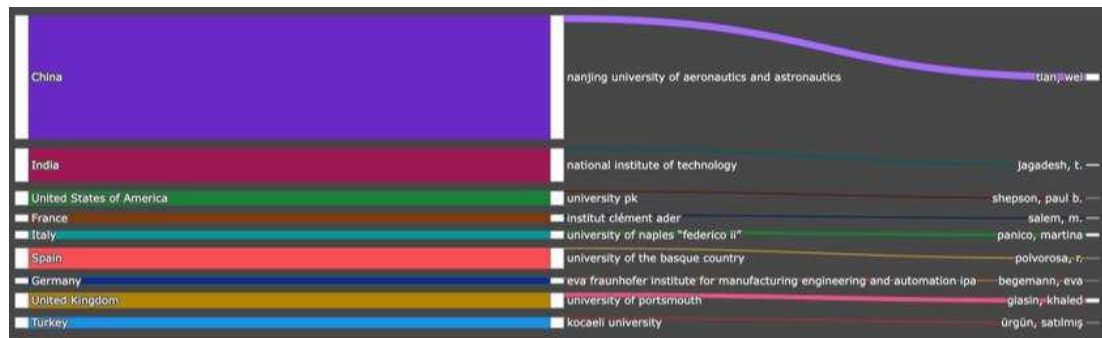
3.2 Top countries and researchers

The PyBibX library also enables the generation of Sankey diagrams, which are particularly effective for visualising the flow and relationships between entities such as authors, countries, and institutions. In this study, two complementary perspectives are examined: the connections between leading countries and their primary research institutions, and the links between individual researchers, their affiliated institutions, and the countries in which they are based. These diagrams provide complementary insights into both the geographical concentration of research activity and the institutional and individual actors driving scholarly contributions.

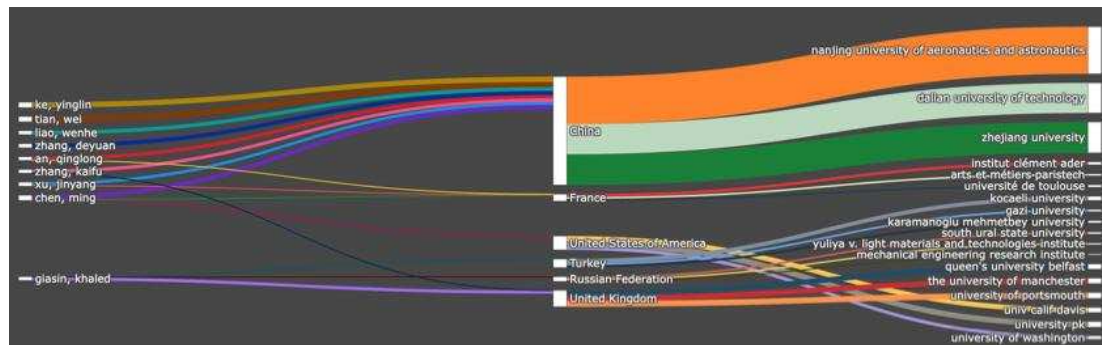
Figure 4 (a) shows the network is strongly dominated by China, which serves as the principal hub linking several prolific authors, including Ke Yinglin (28 publications), Tian Wei (27), Chen Ming (22), Zhang Deyuan (21), Liao Wenhe (20), Zhang Kaifu (18), and An Qinglong (18). This strong national concentration is further reflected in the institutional layer, where Nanjing University of Aeronautics and Astronautics emerges as the most prominent node (250 publications), followed by Zhejiang University (162) and Dalian University of Technology (158). Beyond China, notable secondary hubs include the United Kingdom, led by the University of Portsmouth (31), the University of Manchester (28), and Queen's University Belfast (27), as well as Turkey, where Kocaeli University (22) forms the strongest institutional node. France and the Russian Federation also display visible but comparatively smaller institutional subnetworks. Overall, this diagram highlights the overwhelming centrality of Chinese institutions while also evidencing meaningful contributions from European research centres.

Figure 4 (b) presents a more focused country–institution–author flow, emphasising the leading institutional representatives within each major contributing nation. Once again, China dominates the landscape, with the Nanjing University of Aeronautics and Astronautics prominently linked to Tian Wei, reinforcing the institution's role as a major driver of publication output. Other national

contributions are more distributed, including the National Institute of Technology in India linked to Jagadesh T., University PK in the United States connected to Shepson Paul B., Institut Clément Ader in France associated with Salem M., and the University of Naples Federico II in Italy linked to Panico Martina. Additional visible pathways include the University of the Basque Country in Spain, connected to Polvorosa R., the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Germany, associated with Begemann Eva, the University of Portsmouth in the United Kingdom, linked to Giasin Khaled, and Kocaeli University in Turkey, connected to Urgan Satilmis. By tracing the progression from countries to institutions and then to individual scholars, this diagram offers a more granular perspective on the specific researchers underpinning national and institutional productivity.



(a)



(b)

Fig. 4 Sankey diagrams illustrating research collaboration and contribution patterns across authors, countries, and institutions: (a) flows from leading researchers to their associated countries and subsequently to the most productive institutions, highlighting the strong concentration of output within Chinese universities, particularly the Nanjing University of Aeronautics and Astronautics, Zhejiang University, and Dalian University of Technology; and (b) country–institution–author pathways showing the principal institutional representatives within major contributing nations. Collectively, these views emphasise the dominance of China, while also revealing substantial contributions from the United Kingdom, Turkey, France, the United States, India, Spain, Germany, and Italy, together with the individual researchers underpinning national and institutional productivity.

3. Hybrid Topic Modelling and Expert-Guided Thematic Consolidation

The objective of this stage was to systematically identify the thematic structure of the bibliographic dataset through a hybrid workflow combining exploratory topic modelling, expert-informed theme definition, embedding-based document filtering, subset-level topic modelling, and AI-assisted synthesis.

The analysis began with a corpus-wide exploratory topic modelling stage using the PyBibX *create_topics_from_abstracts()* function applied to the full bibliographic dataset. This function integrates document embeddings generated from abstracts through *create_embeddings()*. To ensure a consistent semantic representation space across the entire corpus and all subsequent filtering stages, the transformer model ‘sentence-transformers/all-MiniLM-L6-v2’ was used throughout the workflow. This model converts each abstract into a dense numerical vector using a Sentence-BERT architecture, positioning semantically similar studies close to one another within a shared embedding space. It was selected because of its demonstrated suitability for semantic similarity analysis, clustering, and scientific metadata retrieval, while maintaining substantially lower computational cost than larger transformer variants [17].

The exploratory modelling stage produced 42 topic clusters, each represented by its most salient keywords. The generated topics showed a strong capacity to separate the literature into technically meaningful areas. Clear clusters emerged around abrasive waterjet machining, laser drilling, EDM and electrochemical machining, conventional drilling mechanics, CFRP/Ti stack drilling, signal-based monitoring, delamination behaviour, ultrasonic-assisted drilling, robotic drilling systems, positional accuracy, helical milling, additive manufacturing, residual stress, and structural inspection methods. A small number of peripheral or weakly defined clusters also appeared, which is expected in unsupervised clustering workflows when sparse or heterogeneous abstracts are present. To illustrate the behaviour of the exploratory clustering stage without overloading the manuscript with the full list of 42 topics, Table II presents the first five representative topic clusters and their most salient keywords.

Table II. Illustrative examples of the first five topic clusters generated through corpus-wide exploratory topic modelling using PyBibX.

Topic	Keywords
1	abrasive, jet, water, awj, surface, parameters, cutting, kerf, awjm, roughness
2	laser, pulse, holes, hole, drilling, processing, taper, micro, power, cooling
3	electrode, micro, machining, edm, discharge, electrochemical, process, electrolyte, holes, hole
4	training, disaster, emergency, medical, fire, aviation, evacuation, patients, safety, team
5	drilling, drill, feed, hole, cutting, tool, force, speed, parameters, surface

A second phase of thematic organisation was then introduced through expert-informed theme definition. Figure 5 shows the general workflow to construct the drilling technologies research landscape. High-level categories were established using three complementary sources: (i) the

exploratory data analysis, (ii) a structured workshop involving six academic researchers, and (iii) direct input from two industrial specialists in aircraft drilling. This triangulated process resulted in robust higher-level themes such as CFRP machining, stack drilling, process optimisation, drilling-induced damage, hole-making methods, in-process and real-time analysis, and sustainability-oriented manufacturing.

Each theme was represented as a curated set of keywords and technical phrases, as shown in Table III. These keyword sets were then projected into the same embedding space defined in the initial corpus-wide modelling stage. Cosine similarity was subsequently computed between each thematic vector and the document embeddings, enabling the retrieval of studies that were semantically aligned with each theme even when exact terminology differed. This step proved particularly valuable for consolidating related topics expressed through multiple lexical forms during the unsupervised clustering stage.

Table III. Expert-informed thematic categories and associated keyword sets derived from three complementary sources: academic workshop discussions, exploratory data analysis (EDA), and industrial partner input. These curated keyword groups were used to construct semantic theme vectors for document retrieval and subset-level topic modelling.

Topic	Keywords academic workshop	Keywords EDA	Keywords industrial partners
CFRP	composite', 'CFRP', 'honeycomb', 'FRP'	carbon fiber reinforced', 'polymer'	-
Stacks	CFRP/Ti', 'stack', 'one-shot', 'interface', 'multi-material'	cfrp ti', 'stacks'	-
Optimisation	tool design optimisation', 'optimisation process parameters'	multi optimization', optimization parameters'	-
Drilling damage	damage-free hole', 'delamination', 'tool wear'	'surface roughness'	burr'
Hole-Making Methods	water jet', 'electric discharge', 'laser cutting', 'electrochemical machining'	vibration assisted'	laser drilling', 'orbital drilling', 'circular milling', 'vibration technology', 'helical milling'
In-process & Real-time analysis	real-time', 'in-process', 'analytics', 'predictions', 'control', 'sensor', 'digital twin', 'digital passport', 'AI'	finite element', 'taguchi grey relational', 'machine learning'	simulation', 'sensor integration', 'data analytics', 'worker guidance', 'data manufacturing'
Eco/Sustainability	recycling', 'waste', 'eco- friendly', 'environmentally friendly', 'cryogenic cooling'	in situ resource utilization'	Co2', 'Green cutting fluids'

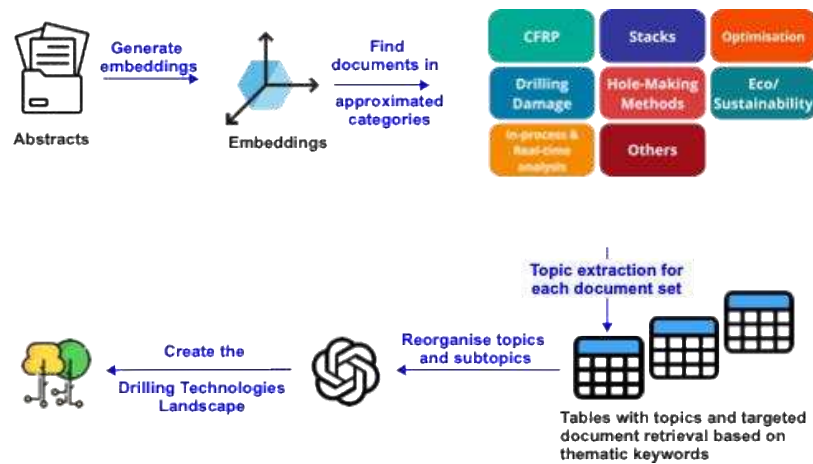


Fig. 5 Workflow illustrating the steps undertaken to construct the drilling technologies research landscape. The process involves automated topic modelling from abstract embeddings, targeted document retrieval based on thematic keywords, thematic topic extraction within document subsets, and iterative refinement using AI-assisted review to improve thematic clarity and structure.

Following this semantic assignment, a dedicated document subset was created for each theme using the PyBibX filtering function. Topic modelling was then applied independently within each thematic subset, rather than across the full corpus. This localised topic detection step improved topic coherence by identifying representative keywords and central studies within a constrained semantic context, thereby reducing cross-theme noise and improving interpretability.

For each thematic subset, two structured outputs were automatically generated: (i) a raw evidence table containing abstract, author keywords, DOI, title, and publication year, and (ii) a topic-enriched table that additionally included the representative topic keywords extracted by PyBibX.

These thematic tables were subsequently used as structured inputs for AI-assisted synthesis using ChatGPT. A fixed prompt instructed the model to jointly analyse all thematic tables, merge overlapping content, eliminate redundancy, and reorganise the results into a maximum of five cohesive and non-overlapping research domains representing the overall drilling technology landscape. In a second step, representative papers were identified for each synthesised topic to strengthen traceability between the final high-level themes and the underlying bibliographic evidence.

Importantly, the role of ChatGPT was restricted to higher-level semantic consolidation of the evidence tables generated through the preceding computational and expert-driven workflow. The final thematic synthesis, therefore, remained firmly grounded in explicit bibliographic evidence, while benefiting from scalable abstraction across overlapping research streams.

As shown in Figure 6, the initially fragmented topic clusters were synthesised into five cohesive research themes, each represented by four core subthemes that capture the dominant directions of the field. To further contextualise this thematic framework, a brief description of each topic is provided below:

1. **Intelligent Monitoring Quality Analytics:** Covers sensor fusion, signal processing, machine learning, and adaptive control for real-time fault detection, tool-condition monitoring, and autonomous quality assurance.

2. **Hybrid Stacks & Multi-Material Drilling:** Focuses on the unique challenges of drilling layered aerospace stacks such as CFRP/Ti, including interface temperature, delamination, burr formation, and sequence effects.
3. **Process Optimisation & Predictive Modelling:** Encompasses statistical, multi-criteria, and AI-based approaches for selecting drilling parameters that optimise hole quality, productivity, and tool life.
4. **Advanced Hole-Making Processes:** Covers non-conventional and hybrid processes such as helical milling, ultrasonic-assisted drilling, EDM, AWJM, and laser-assisted hole generation.
5. **Damage, Surface Integrity & Sustainable Drilling:** Addresses defect mechanisms, hole morphology, thermal damage, lubrication strategies, and environmentally responsible drilling practices.

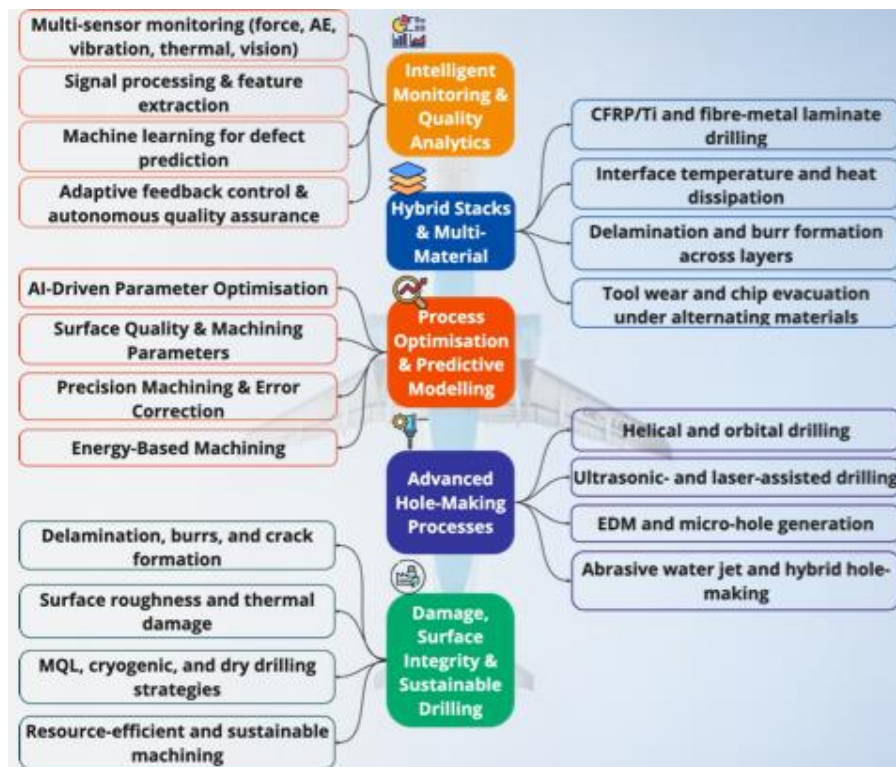


Fig. 6 Workflow illustrating the steps undertaken to construct the drilling technologies research landscape. The process involves automated topic modelling from abstract embeddings, targeted document retrieval based on thematic keywords, thematic topic extraction within document subsets, and iterative refinement using AI-assisted review to improve thematic clarity and structure.

To complement the visual synthesis, Table IV summarises the key research themes, their core focus areas, and representative studies drawn from the literature. These results provide a structured taxonomy of the field, highlighting its evolution from predominantly experimental investigations toward digitally integrated, predictive, and sustainability-oriented drilling solutions.

Table IV. Description of the key research themes, their core focus areas, and representative studies drawn from the literature.

Topic	Description	Relevant references
Intelligent Monitoring & Quality Analytics	<p>This topic focuses on the use of sensor-enabled monitoring, data-driven modelling, and artificial intelligence to improve drilling-process reliability, hole quality, and decision-making in advanced manufacturing. Across the dataset, the dominant emphasis is on real-time sensing, tool-condition monitoring, surface-quality prediction, and AI-assisted process optimisation, particularly for aerospace drilling and CFRP stack applications.</p> <p>Key Themes</p> <ul style="list-style-type: none"> • In-process sensing and monitoring: Real-time acquisition of process signals using force, tactile, vibration, and vision-based sensing to detect faults and process anomalies during drilling and robotic manufacturing. • Signal interpretation and feature learning: Extraction of meaningful process signatures from sensor streams, including minimum sufficient signal conditions and latent features for incidence recognition. • Machine learning and neural networks: Strong use of ANNs, backpropagation neural networks, autoencoders, and memory-based neural networks for predicting surface roughness, hole diameter, and tool wear evolution. • Tool wear and defect prediction: A major theme focused on non-intrusive monitoring of wear progression in CFRP/CFRP stack drilling and automated aerospace drilling systems. • Digital integration and smart manufacturing: Emerging integration with digital twins, digital threads, and Industry 4.0-enabled robotic systems for closed-loop process optimisation and quality enhancement. 	<p>“Real-Time Fault Detection in Robotic Manufacturing Using High-Bandwidth Event Vision-Based Tactile Sensing” [18]</p> <p>“Smart Tool Wear Monitoring of CFRP/CFRP Stack Drilling Using Autoencoders and Memory-Based Neural Networks”[19]</p> <p>“Machine learning approach in non-intrusive monitoring of tool wear evolution in massive CFRP automatic drilling processes in the aircraft industry” [20]</p> <p>“Estimating high precision hole diameters of aerospace alloys using artificial intelligence systems: a comparative analysis of different techniques” [21]</p> <p>“Multimodal 1D CNN for delamination prediction in CFRP drilling process with industrial robots” [22]</p>
Hybrid Stacks & Multi-Material Drilling	<p>This topic focuses on the drilling of layered composite–metal stacks, particularly CFRP/Ti, CFRP/Ti6Al4V, CFRP/Al, and stacked aluminium structures used in aerospace assembly. The papers in this cluster consistently address the complex thermo-mechanical interactions at material interfaces, where abrupt changes in stiffness, thermal conductivity, and chip formation behaviour intensify defect formation and compromise hole integrity.</p> <p>Key Themes</p> <ul style="list-style-type: none"> • Interface thermal effects: Studies the role of interface temperature, heat accumulation, and thermal softening in ultrasonic-assisted and conventional drilling of CFRP/Ti stacks. • Delamination and burr suppression: Strong focus on controlling entrance delamination, interlayer burrs, and exit defects through process strategies such as preload pressing, adaptive feed design, and damage-suppression methods. • Drilling sequence and stack mechanics: Investigates how drilling order, layer stiffness, and material sequence affect cutting responses, thrust force, non-coaxiality, and hole quality. • Interlayer gap evolution and control: A major research direction centred on real-time measurement, analytical modelling, and suppression of interlayer gaps, which directly govern burr formation and assembly cost. • Precision hole-making in aerospace stacks: Includes advanced methods such as automated helical milling with feedback compensation to minimise diameter error and ensure fastener-hole fit in composite/metal aerostructures. 	<p>“A critical review addressing conventional twist drilling mechanisms and quality of CFRP/Ti stacks” [23]</p> <p>“The interface temperature and its influence on surface integrity in ultrasonic-assisted drilling of CFRP/Ti stacks” [24]</p> <p>“Influence of flute number and stepped bit geometry when drilling CFRP/Ti6Al4V stacks” [25]</p> <p>“Material recognition method to enable adaptive drilling of multi-material aerospace stacks” [26]</p> <p>“Study on tool deflection compensation method based on cutting force observer for orbital drilling of CFRP/Ti stacks” [27]</p>
Process Optimisation & Predictive Modelling	<p>This topic focuses on the systematic optimisation of drilling and hole-making parameters using statistical design, machine-learning prediction, and metaheuristic search algorithms. The studies in this cluster consistently aim to balance hole quality, surface integrity, material removal rate, tool wear, and process productivity, particularly for difficult-to-machine aerospace materials such as Ti6Al4V, Inconel 718, CFRP, and hybrid stacks.</p> <p>Key Themes</p> <ul style="list-style-type: none"> • Statistical design and response modelling: Extensive use of Taguchi design, Box–Behnken RSM, ANOVA, regression modelling, and orthogonal arrays to quantify parameter effects and establish predictive response models. • Metaheuristic and evolutionary optimisation: Frequent use of NSGA-II, PSO, grey wolf optimiser, harmony search, whale optimisation, and custom search algorithms to identify Pareto-optimal drilling conditions. • Machine-learning-assisted prediction: Strong integration of ANN, Bayesian neural networks, Cubist regression, RBF networks, and GAN-enhanced datasets to model nonlinear relationships among process variables and machining outcomes. • Multi-objective trade-off analysis: Simultaneous optimisation of delamination, roughness, kerf taper, MRR, tool life, and energy 	<p>“A hybrid machine learning approach to optimize kerf quality in AWJM of Ti-6Al-4V/CFRP/Al7075 stacks” [28]</p> <p>“Optimization of drilling parameters on delamination and burr formation in drilling of neat CFRP and hybrid CFRP nano-composites” [29]</p> <p>“Deep hole electrical discharge machining of nickel-based Inconel-718 alloy using response surface methodology” [30]</p> <p>“Grey relational analysis-based genetic algorithm optimization of electrical discharge drilling of Nimonic-90 superalloy” [31]</p>

	<p>consumption, often using Pareto fronts and ranking methods such as Entropy-TOPSIS or Grey Relational Analysis.</p> <ul style="list-style-type: none"> • Productivity–quality balancing in aerospace machining: A recurring focus on optimising process windows for Inconel, titanium alloys, superalloys, and CFRP drilling under industrial productivity constraints. 	<p>“Multi-objective optimisation of cutting parameters for drilling-induced damages and thrust force in AFRP drilling” [32]</p> <p>“Optimization of Abrasive Water-Jet Machining Process Parameters on Onyx Composite” [33]</p>
<p>Advanced Hole-Making Processes</p>	<p>This topic focuses on advanced, non-conventional, and hybrid hole-generation technologies developed for high-precision, high-aspect-ratio, and low-damage machining in difficult aerospace materials. The documents in this topic show a clear progression from stand-alone laser, EDM, ECM, and AWJM processes toward hybrid, assisted, robotic, and model-driven hole-making strategies, highlighting the field’s transition into a multi-physics manufacturing ecosystem.</p> <p>Key Themes</p> <ul style="list-style-type: none"> • Laser-based micro- and precision drilling: Covers trepanning, helical, percussion, water-jet-guided, picosecond, and ultrashort pulse laser drilling, with strong emphasis on taper, HAZ, recast, and film-cooling-hole quality. • EDM / ECM / plasma micro-hole fabrication: Includes micro-EDM, shaped-tube ECM, PA-STEM, post-ECM finishing, and ultra-large aspect-ratio electrochemical drilling. • Hybrid and assisted hole-making: A major emerging direction involving laser + side milling, laser + ECM, LBMM + μEDM, ultrasonic-assisted drilling, waterjet-assisted laser, and robotic compound drilling. • Helical milling and orbital hole generation: Strong representation of helical milling, hole-diameter deviation control, force fluctuation modelling, and aerospace-quality CFRP hole production. • In-process modelling, compensation, and metrology: Increasing use of AE-based depth sensing, SVR estimators, point-cloud wear prediction, FEM/SPH simulation, and geometry compensation models. 	<p>“Experimental study on robot laser and side-milling compound technology for drilling of CFRP/TC4 laminated stacks” [34]</p> <p>“Fabrication and quality improvement of film cooling holes via picosecond laser drilling assisted by waterjet and post-electrochemical machining” [35]</p> <p>“Plasma-assisted shaped tube electrochemical machining for ultra-large aspect ratio holes: {Radical} field shielding mechanisms and ultra-low electrode wear” [36]</p> <p>“Radial tool wear analysis and compensation strategy for microhole arrays in sequential hybrid laser beam micromachining (LBMM) and micro-EDM” [37]</p> <p>“Investigation on deviation of the hole diameter in helical milling” [38]</p> <p>“Study of Surface Topography in Abrasive Water-Jet Machining of Carbon Foam” [39]</p>
<p>Damage, Surface Integrity & Sustainable Drilling</p>	<p>Focused on understanding and mitigating drilling-induced defects, preserving subsurface integrity, and advancing environmentally responsible hole-making strategies for aerospace materials. This area integrates defect mechanics, thermal and tribological effects, lubrication optimisation, and sustainable process design to improve hole quality while reducing tool wear, energy demand, and environmental burden.</p> <p>Key Themes</p> <ul style="list-style-type: none"> • Damage Mechanisms and Hole Integrity: Strong emphasis is placed on delamination, burr formation, interface decohesion, white-layer generation, microcracking, residual stresses, and dimensional deviation, particularly in CFRP, titanium alloys, and hybrid stacks. • Surface Integrity Preservation: Research addresses surface roughness, subsurface microstructural alterations, hardness variation, residual stress evolution, and fatigue-critical defects that directly influence structural reliability in aerospace assemblies. • Sustainable Cooling and Lubrication: There is increasing adoption of dry drilling, compressed air, MQL, cryogenic cooling, hybrid CryoMQL, and high-pressure cooling to minimise thermal damage, reduce friction, improve chip evacuation, and lower environmental impact. • Tool Wear and Resource Efficiency: Studies focus on extending tool life through coatings, textured tools, advanced geometries, and assisted drilling methods, reducing material waste, downtime, and consumable usage. • Intelligent Damage Monitoring: Acoustic emission, force sensing, FEM, and digital monitoring approaches are increasingly integrated to predict damage evolution and enable adaptive, sustainability-oriented process control. <p>Future Directions:</p> <ul style="list-style-type: none"> • Greater integration of sustainable cooling strategies with defect prediction models. • Real-time AI-driven monitoring for adaptive damage suppression and tool life optimisation. • Lifecycle-based evaluation linking drilling-induced damage, fatigue life, and environmental footprint. • Expanded use of low-energy assisted drilling methods for composite and hybrid aerospace stacks. 	<p>“Experimental Assessment of Hole Quality and Tool Condition in the Machining of an Aerospace Alloy” [40]</p> <p>“Analysis of surface integrity in drilling carbon fiber reinforced polymer composite material under various cooling/lubricating conditions” [41]</p> <p>“Fabrication, machining (dry vs. cryogenic) and life cycle analysis of hybrid titanium composite laminates (HTCL)” [42]</p> <p>“Improvement of machinability of Ti and its alloys using cooling-lubrication techniques: A review and future prospect” [43]</p> <p>“Sustainable Processes in Aluminium, Magnesium, and Titanium Alloys Applied to the Transport Sector: A Review” [44]</p> <p>“Holistic review of drilling on CFRP composites: Techniques, FEM, sustainability, challenges, and advances” [45]</p> <p>“High speed cryogenic drilling of Ti-6Al-4V alloy under high pressure coolant conditions” [46]</p>

The concept co-occurrence mapping of the 260 semantically aligned publications reveals that intelligent monitoring and quality analytics in advanced drilling are evolving from isolated sensor-based quality inspection toward increasingly integrated cyber-physical manufacturing ecosystems. The dominant clusters show strong emphasis on signal-based process monitoring, tool wear prediction, surface integrity assessment, vision-based hole-quality inspection, robotic drilling cells, and data-driven optimisation of drilling parameters. Beyond these established directions, the thematic structure also highlights emerging research trajectories that make the field increasingly forward-looking. In particular, the growing presence of robotic drilling systems, in-situ geometric inspection, and predictive fusion-network architectures suggests a clear transition toward adaptive process-control frameworks, where sensing, modelling, and parameter correction are progressively integrated in near real time. This evolution is further reinforced by the increasing adoption of hybrid data-driven and process-informed modelling strategies, which combine process mechanics, signal analytics, and machine learning to improve robustness under limited-data and multi-material aerospace drilling conditions.

From a broader manufacturing perspective, these developments strongly intersect with sustainable machining objectives. Intelligent monitoring frameworks are increasingly being used not only to improve hole quality and process reliability, but also to reduce tool waste, minimise scrap generation, decrease unnecessary rework, and optimise energy-intensive drilling cycles in CFRP/Ti and multi-material stack applications. The integration of adaptive feedback, predictive wear modelling, and process-parameter optimisation is particularly relevant for green aerospace manufacturing, as these technologies enable adaptive feed-rate control, reduction of defective holes, extension of tool life, and more efficient use of cutting resources. Consequently, intelligent quality analytics is emerging as a key enabler for sustainable and resource-efficient drilling systems, bridging smart manufacturing paradigms with the growing need for environmentally responsible aerospace production.

Table V. Description of each cluster from the concept co-occurrence mapping for the 260 semantically selected publications on intelligent monitoring and quality analytics

Cluster	Name	Description	Key Themes	Representative Papers
Blue	Process Parameters and Surface Integrity	Focuses on process-parameter optimisation, surface roughness prediction, machining performance modelling, and data-driven quality estimation in advanced drilling systems.	Surface roughness, machining performance, process parameters	[11,47,48]
Green	Robotic Drilling, Vision Inspection and State Control	Represents robotic drilling systems, end-effector control, position-error compensation, vision-based hole inspection, and lightweight AI-enabled state classification for automated aerospace drilling cells.	Robotic drilling, vision-based inspection, state classification, end-effector control	[49–51]
Purple	Signal-Based Process Monitoring and Stack Drilling	Covers minimum sufficient signal conditions, one-shot drilling monitoring, stack-drilling diagnostics, and smart tool wear monitoring for CFRP stacks.	Signal features, stack drilling, tool wear monitoring	[19,52,53]
Yellow	Tool Wear and Multi-Material Monitoring	Focuses on non-intrusive tool wear monitoring, multi-material stage analysis, and machine-learning strategies for wear-state classification and progression analysis.	Tool wear, multi-material analysis, non-intrusive monitoring	[19,20,54]
Red	Advanced Drilling Optimisation and Laser Processing	Represents optimisation strategies, dimensional in-situ inspection, and hybrid fiber laser drilling for advanced aerospace and precision hole-making applications.	Optimisation, laser drilling, dimensional inspection	[55–57]
Turquoise	Surface Quality Analytics and Fusion Networks	Captures deep-learning fusion networks, drilling surface quality analysis, and hybrid neural architectures for predictive manufacturing analytics.	Fusion networks, surface quality, predictive analytics	[48,58,59]

Orange	Hole Quality Prediction and In-Situ Evaluation	The central predictive-quality cluster focused on hole-quality forecasting, deep-hole drilling diagnostics, and in-situ evaluation of cutting and geometric quality.	Hole quality, prediction, deep-hole drilling	[51,60,61]
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6. Limitations

Despite the systematic multi-stage workflow adopted, several limitations should be acknowledged.

First, the final corpus remains dependent on the initial keyword strategy and database query design. Although the search string was iteratively refined to maximise thematic coverage, relevant studies using alternative terminology, domain-specific jargon, or emerging nomenclature may still have been missed, as is inherent to lexically defined bibliographic retrieval.

Second, the analysis may reflect database-level coverage biases related to journal inclusion policies, language restrictions, and publisher representation, potentially under-representing regional, industrial, or highly application-specific contributions.

Third, while topic discovery was supported through embedding-based unsupervised topic modelling, the subsequent manual consolidation into higher-level themes introduces an unavoidable interpretive component. Although expert refinement improved semantic coherence and engineering relevance, alternative expert groups might reasonably define different thematic boundaries or assign borderline studies differently.

A further limitation is that the methodology relies primarily on published academic literature, which may not fully represent industrial drilling and machining practice, where optimisation strategies, proprietary tooling solutions, and sustainability trade-offs are often embedded in confidential reports or undocumented operational know-how. The resulting thematic structure should therefore be interpreted as a representation of the documented scientific discourse, rather than a complete reflection of industrial reality.

An additional methodological constraint concerns the minimum corpus size required for stable topic discovery. Because embedding-based clustering requires sufficient semantic diversity, subsets with fewer than approximately 20 documents may produce fragmented or weakly supported themes. The workflow is therefore better suited to research areas with sufficient bibliographic density than to highly niche or emerging topics.

Finally, the AI-assisted synthesis stage supported interpretive consistency and summarisation efficiency but remained dependent on curated inputs and expert supervision. Accordingly, AI outputs were used as decision-support tools rather than autonomous analytical agents.

7. Conclusion

This review systematically maps the evolving landscape of drilling technologies in aircraft manufacturing, highlighting the field's progression towards increasingly intelligent, adaptive, and sustainability-oriented hole-making systems. By integrating bibliometric analysis, semantic topic modelling, and expert-guided taxonomy refinement, the study establishes a robust hybrid review methodology capable of revealing both intellectual structures and industrially relevant technological

trajectories. The combination of computational evidence mapping with domain expertise ensured that the resulting synthesis remained methodologically rigorous while retaining strong aerospace manufacturing relevance.

The analysis generated several key contributions. First, the hybrid methodology enabled the development of a coherent five-theme taxonomy spanning intelligent monitoring and quality analytics; hybrid stacks and multi-material drilling; process optimisation and predictive modelling; advanced hole-making processes; and damage, surface integrity, and sustainable drilling. These themes collectively capture the dominant technological pathways shaping contemporary aerospace drilling research. Second, the review identified a clear technological transition from conventional parameter-based optimisation towards digitally enabled drilling systems characterised by in-process sensing, adaptive control, machine-learning-assisted prediction, and autonomous quality assurance. Third, the temporal and bibliometric evidence highlighted the growing strategic importance of hybrid stack machining, non-conventional hole-making methods, sustainable lubrication strategies, and AI-driven process intelligence, alongside the emergence of influential academic research networks.

Looking forward, the hybrid review framework demonstrated here can be extended beyond drilling to adjacent aerospace manufacturing domains, including fastening systems, metrology, robotic assembly, and multi-process digital manufacturing. Future research should particularly explore the integration of digital twins, explainable AI, and closed-loop machining architectures to support autonomous and resilient aircraft production systems.

In conclusion, this work provides both a comprehensive synthesis of state-of-the-art aerospace drilling technologies and a scalable evidence-based methodology for research mapping in high-value manufacturing. The findings offer a structured roadmap for future scientific investigation while supporting strategic technology adoption in next-generation aerospace production environments.

8. Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT to iteratively review and reorganise the Drilling Technologies Landscape. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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