A HUMAN-CENTERED SYSTEMS ENGINEERING APPROACH FOR INTEGRATING ARTIFICIAL INTELLIGENCE IN AVIATION: A Review of AI Systems

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Abstract

The introduction of Artificial Intelligence (AI) Systems in the design of new aeronautical products impacts not only the project architecture regarding the hardware and software but also inserts new layers of complexity into Systems Engineering methods to evaluate the entire product life cycle. More specifically related to the end users within the scope of the study, the pilots, the inclusion of AI Systems also impacts the human factors aspects addressed in Systems Engineering methods, as well as the human-machine interaction. Issues such as information ambiguities, lack of pilot situational awareness and system understanding can be presented in various flight events and are concerns of the aeronautical industry and certification authorities. Human-AI Teaming (HAT) concepts are the basis of understanding how the flight crew can use AI systems in aviation, enabling them to achieve their full potential. As such, this paper reviews the main AI Systems research in aviation and their relationship with human factors and systems engineering. It discusses the main outcomes, challenges, and recommendations for human-AI systems integration. The research shows that there has been a considerable increase in the study in the last decade, most focused on machine learning applications that could be used not only in the flight deck assisting the pilot but also as a ground or real-time analysis of the workload and situational awareness. It is discussed how these AI Systems could be even more implemented in aviation in a specific context of flight operations, utilizing current patterns, for example, from the flight manuals, that could feed data regarding AI Systems, and therefore being part of the assistance of the flight crew.

Keywords: Human-AI teaming, flight deck, AI systems design, human factors, systems engineering.

1. Introduction

The aviation industry contributes significantly to global technological innovation. Its characteristics of seeking continuous improvement, engaging the various stakeholders (airlines, manufacturers, customers, and national regulatory agencies), and constant research and development allow global air transport to become increasingly safe, efficient, and accessible.

Regarding this continuous evolution, the latest technological revolution in the aviation industry is the growth of Artificial Intelligence (AI) and its potential to transform the world of aviation. With this, AI allows intelligent systems to be created that can provide advanced solutions to the end user, optimizing aircraft performance and increasing safety in an unprecedented way. However, the development of artificial intelligence in aviation also poses new challenges and issues that need to be addressed [1].

From this scope, incorporating AI systems in the design considerably changes the systems engineering methods. With the changing landscape of technology and the rapid growth of practically executed AI in pursuit of autonomous systems, it is imperative to innovate Systems Engineering methodologies, including new approaches for designing, verifying, and validating systems. Innovation is necessary since the developing foundations of Systems Engineering and its methods were not intended to design systems equipped with the latest advances in AI, including machine learning (ML), deep learning (DL), diverse autonomous systems, or multi-domain operations [2].

In this context, as Borst, Mulder, and Van Paassen [3] presented, “although the progressive development of cockpit automation has resulted in many improvements in terms of safety and pilot workload, new problems, related to technological advances in pilot support systems, have also emerged.”

Since much information is hidden from the pilot, the cockpit has become prone to challenges such as information ambiguity and misunderstanding between the pilot and the automated avionics systems. This phenomenon is characterized by a lack of situational awareness for the pilot and has become a new cause of accidents [4].

Therefore, pilots are sometimes unaware of the current flight situation, which can be caused by automation. With the advancement of new automatic systems, artificial intelligence is an increasing contributing factor to this problem.

Artificial intelligence and its current and future applications in aviation could present several gains throughout the product design process. More specifically, it is expected to ensure that the pilot can continue to be a key player in flight control, but with increasingly robust and precise information that allows for an increase in situational awareness and facilitates the decision-making process. This assessment of decision-making and the evolution of pilot performance with applied artificial intelligence can be done with the essential tests and validations of Systems Engineering.

Therefore, this paper's objective is to systematically review the impact of integrating AI systems on flight crew performance, addressing considerations and requirements for using AI systems in the flight deck.

A literature review will be conducted regarding systems engineering and human factors research to evaluate the impact of integrating AI systems on flight crew performance. The review will also elaborate a systematic review of AI systems research in aviation, identifying the state-of-the-art in these concepts and potential opportunities for AI integration in flight operations. Thus, existing flight crew interactions with AI systems will be analyzed, considering the concepts of human factors and the impact of AI on pilots' workload, situational awareness, and decision-making processes.

It is expected to identify opportunities for improvement in AI system design processes. This will provide practical recommendations for successfully implementing AI systems that effectively improve decision-making and pilot performance.

By exploring the Human-Centered Systems Engineering approach and integration of AI in aviation, more specifically in the human-machine interface on the flight deck, this study aims to contribute to the development of AI-driven systems that should be required to be helpful in supporting pilots' decision-making, constantly increasing the human performance and flight situational awareness.

In this paper, the methodology in Section 2 will address how the systematic review was elaborated and the means to indicate the most important studies on AI Systems. The bibliometric and content analysis is presented in Section 3. Section 4 presents the discussion and additional considerations.

2. Methodology

The research seeks to map the state-of-the-art in Systems Engineering and Human Factors, thus considering new lines of research that deal with this integration, such as Human Systems Integration (HSI) and human-AI teaming (HAT).

The research will be based on two fronts of systematic literature review with the same methodology: We will use the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach [8, 9]. The first, in section 2.1, will address articles related to the disciplines of Systems Engineering and Human Factors and its subtopics of Human Systems Integration and human-AI teaming.

In section 2.2, after searching more focused on the concepts of Systems Engineering, Human Factors, and their developments, we understand that it is necessary to carry out a dedicated research string for AI Systems studies on the flight deck since the most significant number of studies is very recent. These studies are not necessarily intertwined with the concepts of Systems Engineering.

In section 3, a bibliometric analysis is developed using Microsoft Excel software and VOSViewer 1.6.20 software.

The main articles were defined based on the context of AI Systems' application on the flight deck and the number of citations.

Starting from the systematic review, the results regarding Systems Engineering methodologies, human factors, and AI systems in aviation are analyzed, identifying the main concepts and potential opportunities for AI integration in the flight deck. Thus, existing flight procedures and interactions with AI systems are discussed, considering the concepts of human factors and the impact of AI on pilots' workload, situational awareness, and decision-making processes.

2.1 Human Systems Integration and Correlated Themes - Systematic Literature Review

In the context of Human Systems Integration and correlated themes, the most relevant articles were selected with a timespan from 1963 until 2024, representing approximately 61 years of international scientific production. The research was carried out in the Scopus [31], Web of Science [32], and IEEE Xplore Digital Library [33] databases (accessed during April 2024 and updated until May 23rd, 2024). These scientific databases returned 451 results, selected from journal articles and conference proceedings (267 from Scopus, 59 from WoS, and 125 from IEEE).

From the compiled database, 34 publications were removed (20 from Scopus, 4 from WoS, and 10 from IEEE) from the compiled database due to duplicates or abstracts with content that were out of the scope of this research. Figure 1 presents a flowchart with the PRISMA methodology for selecting articles.

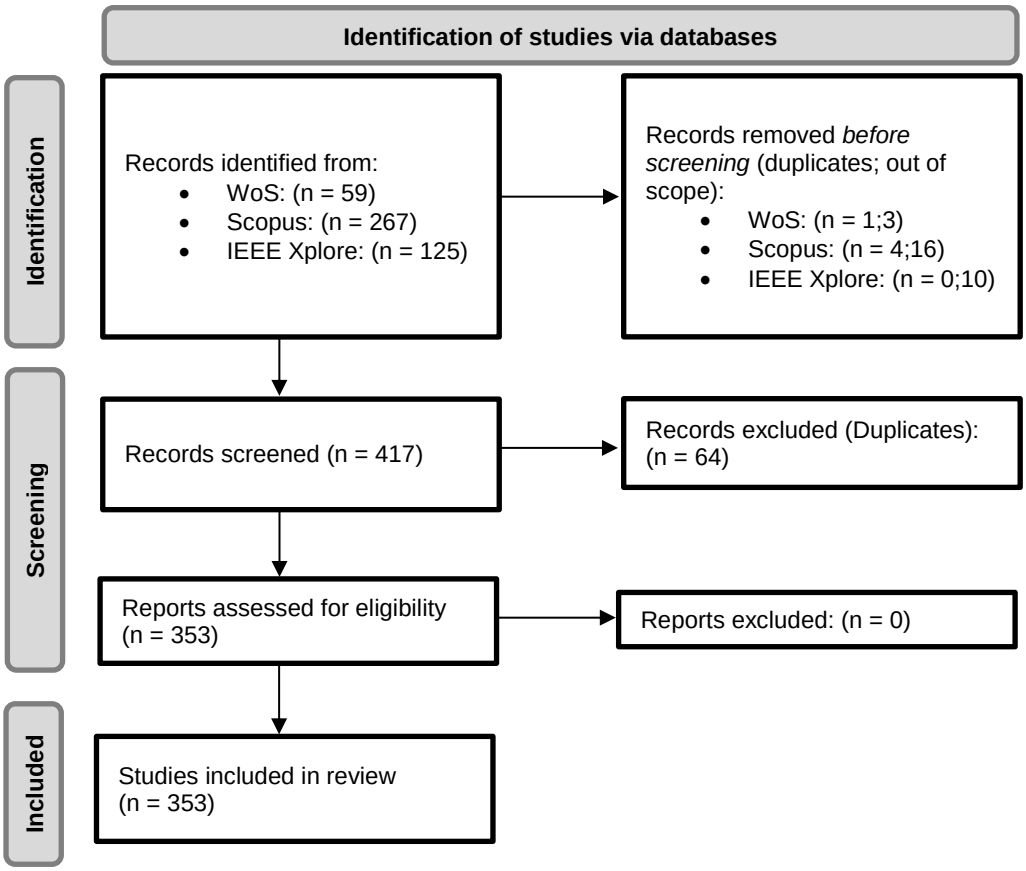

Figure 1 – PRISMA Flowchart – Human Systems Integration and correlates database

The research was based on the following keywords: “systems engineering”, “system of systems”, “SoS”, “systems integration”, “human systems”, “human-centered”, “human-AI teaming”, “human - machine teaming”, “human-machine interface”, “human factors”, “aviation”, “aircraft”, “airplane”, “aeronautics”, and “aerospace”.

From there, all duplicate and out-of-scope articles were removed from each database, and finally, all databases were merged. The papers' eligibility was assessed by analyzing the title and abstract and comparing the keywords with those used in the research.

Table 1 displays the results of the research strings carried out in the different databases and the final compilation results. The research strings were delimited based on the results of titles, abstracts, or keywords of articles published in journals and conference proceedings.

Table 1 – Results of databases compilation

Database	String/Comments	Total	Excluded	Motive	Results
IEEE Xplore	("Systems Engineering" OR "System of System*" OR "SoS" OR "systems integration") AND ("Human systems" OR "Human-centered" OR "Human-Centred" OR "Human-AI Team*" OR "Human-Machine Team*" OR "Human-Machine Interface" OR "Human Factors") AND (aviation OR aircraft* OR airplane* OR aeronautic* OR aerospace)	125	10	Out of scope	115
Scopus	("Systems Engineering" OR "System of System*" OR "SoS" OR "systems integration") AND ("Human systems" OR "Human-centered" OR "Human-Centred" OR "Human-AI Team*" OR "Human-Machine Team*" OR "Human-Machine Interface" OR "Human Factors") AND (aviation OR aircraft* OR airplane* OR aeronautic* OR aerospace)	267	4 16	Duplicate Out of scope	247
WoS	("Systems Engineering" OR "System of System*" OR "SoS" OR "systems integration") AND ("Human systems" OR "Human-centered" OR "Human-Centred" OR "Human-AI Team*" OR "Human-Machine Team*" OR "Human-Machine Interface" OR "Human Factors") AND (aviation OR aircraft* OR airplane* OR aeronautic* OR aerospace)	59	1 3	Duplicate Out of scope	55
Total		451	34		417
	Removed duplicates after databases compilation		64	Duplicate	
Final		451	98		**353**

The data was saved and processed as follows:

- In the Zotero software, extractions from the WoS, Scopus, and IEEE databases were analyzed and merged to include a single set of data;
- From this, the data was exported to Microsoft Excel in XLSX format, where it is possible to carry out additional processing, which will be presented in Section 3, with the bibliometric analysis.

In this way, statistics were compiled in this software, and based on this data, we explored quantitative aspects related to publications and authors. The bibliometric analysis was composed of the following:

- General sample information: annual scientific production, citations by year of publication;
- Analysis of the authors who publish the most in the area;
- Analysis of the most relevant journals;
- Keyword analysis: frequent words and co-occurrence networks.

The number of citations for each reference was compared to those presented on Google Scholar to validate the results. If the results diverged, the result with the highest number of citations prevailed.

2.2 AI Systems on Flight Deck - Systematic Literature Review

In the context of AI systems on the flight deck, the most relevant articles were selected with a timespan from 1974 until 2024, representing approximately 50 years of international scientific production. The research was also carried out using the Scopus, Web of Science, and IEEE Xplore Digital Library databases (accessed during April 2024 and updated until May 23rd, 2024). These scientific databases returned 653 results, selected from journal articles and conference proceedings (348 from Scopus, 105 from WoS, and 200 from IEEE).

From the compiled database, 54 publications were removed (28 from Scopus, 4 from WoS, and 22 from IEEE) due to duplicates or due to having abstracts or content that were out of the scope of this research. Figure 2 exemplifies the PRISMA flowchart.

The research was based on the following keywords: “Human-AI teaming”, “Human-machine teaming”, “intelligent”, “AI”, “AI-driven”, “AI-assisted”, “Generative AI”, “ chatbot”, “ChatGPT”, “machine learning”, “deep learning”, “Artificial Intelligence”, “aircraft”, “aviation”, “aeronautics”, “airplane”, “aerospace”, “pilot”, “flight deck” , and “cockpit”.

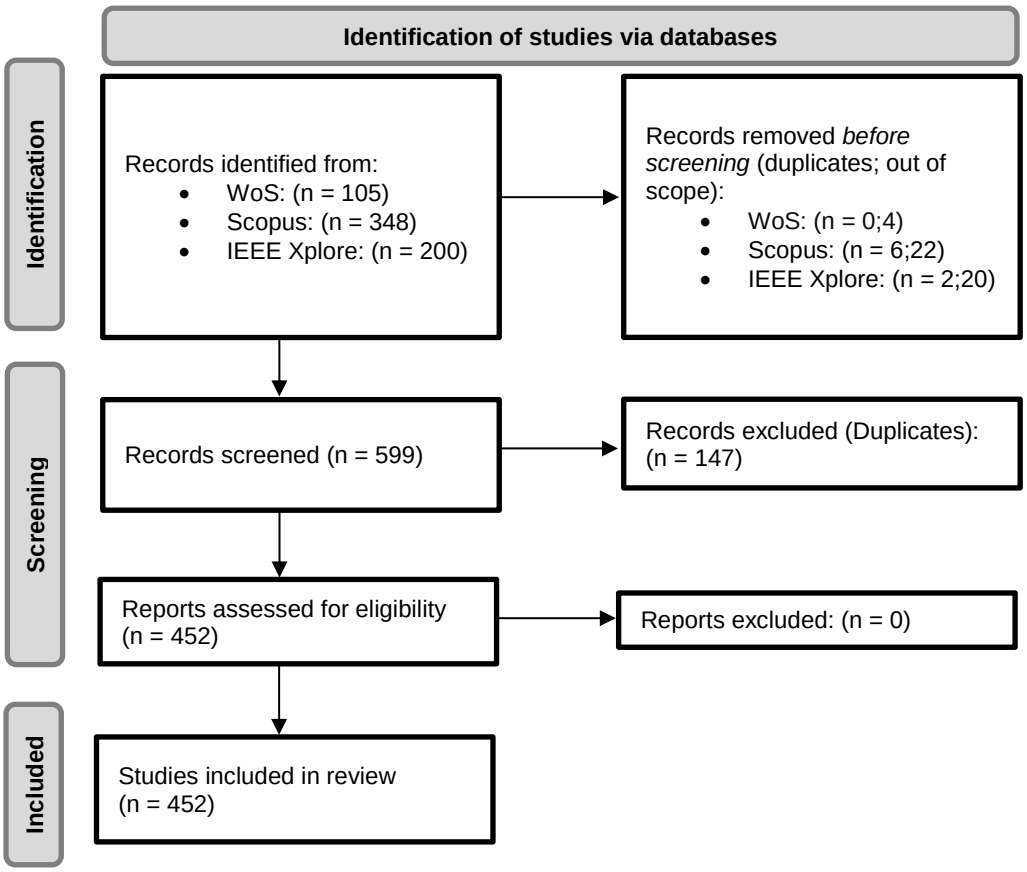

Figure 2 – PRISMA Flowchart – AI Systems Database

Table 2 displays the results of the research strings carried out in the different databases and the compilation's final results.

Table 2 – Results of databases compilation

Database	String/Comments	Total	Excluded	Motive	Results
IEEE Xplore	("Human-AI team*" OR "Human-machine team*" OR intelligent OR “AI” OR "AI-driven" OR "AI-assisted" OR "Generative AI" OR chatbot OR "ChatGPT" OR "machine learning" OR "deep learning" OR "Artificial intelligence") AND (aircraft* OR aviation OR aeronautic* OR airplane* OR aerospace OR *pilot*) AND ("flight deck*" OR cockpit*)	200	2 20	Duplicate Out of scope	178
Scopus	("Human-AI team*" OR "Human-machine team*" OR intelligent OR “AI” OR "AI-driven" OR "AI-assisted" OR "Generative AI" OR chatbot OR "ChatGPT" OR "machine learning" OR "deep learning" OR "Artificial intelligence") AND (aircraft* OR aviation OR aeronautic* OR airplane* OR aerospace OR *pilot*) AND ("flight deck*" OR cockpit*)	348	6 22	Duplicate Out of scope	320
WoS	("Human-AI team*" OR "Human-machine team*" OR intelligent OR “AI” OR "AI-driven" OR "AI-assisted" OR "Generative AI" OR chatbot OR "ChatGPT" OR "machine learning" OR "deep learning" OR "Artificial intelligence") AND (aircraft* OR aviation OR aeronautic* OR airplane* OR aerospace OR *pilot*) AND ("flight deck*" OR cockpit*)	105	4	Out of scope	101
Total		653	54		599
	Removed duplicates after databases compilation		147	Duplicate	
Final		653	201		**452**

The data was processed and treated in Microsoft Excel, Zotero, and VOSviewer software in the same way as presented in section 2.1.

Relevant information is obtained through a bibliometric analysis to understand the main topics in AI Systems being researched, allowing us to discuss the next steps regarding AI systems development.

3. Bibliometric Analysis

A bibliometric analysis was also carried out to identify the main trends in these research fields. Bibliometric analysis is relevant as it allows us to recognize, evaluate, and understand the literature within the research field [10]. In this paper, it will allow us to make a connection between the literature review on Human Systems Integration and the literature review based on AI Systems, mainly on the flight deck.

3.1 Human Systems Integration

Initially, as presented in section 2.1, 353 results from the database compiled for Human Systems Integration were analyzed. Figure 3 presents a graph with the annual evolution of publications on this topic and the total number of citations according to the extracted and compiled research algorithm.

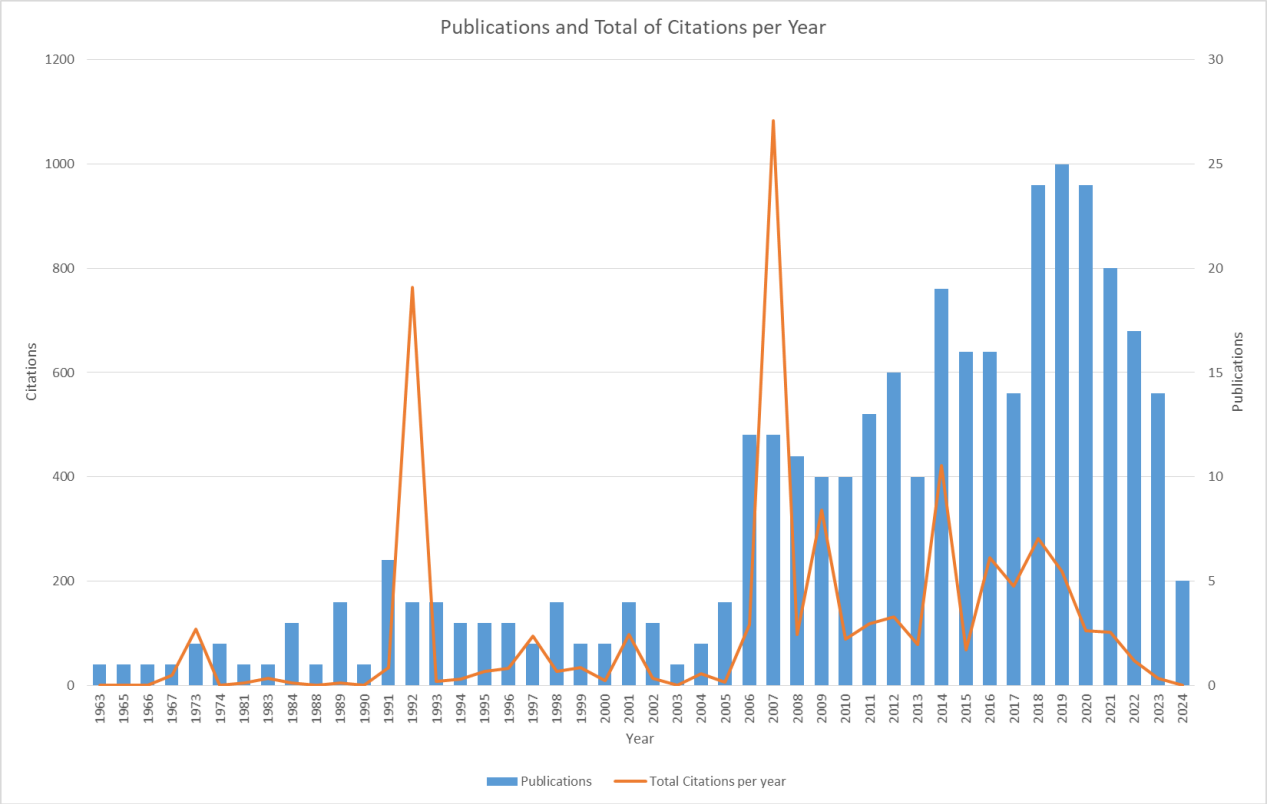

Figure 3 – Publications and a total of citations per year (HSI and correlates)

Figure 3 shows that the number of publications on the topic has increased recently, peaking between 2018 and 2020. From 2021 onwards, a decreasing oscillation in the number of publications has been observed, which is also related to the effects of the COVID-19 pandemic faced in this recent cycle and which impacted the international scientific production.

Furthermore, the peaks in citations on the topic that occurred in 1992 (764 citations) stand out, with the main contribution from Hill et al. [11]; and in 2007 (1084 citations), with the main contributions from Miller & Parasuraman [12] and Rovira, McGarry & Parasuraman [13]. Table 3 presents the 20 most cited articles based on the research algorithm.

Table 3 – Most cited articles for HSI and correlates research

Order	Title	Ref.	Citations
1	Comparison of four subjective workload rating scales	[11]	594
2	Designing for flexible interaction between humans and automation: Delegation interfaces for supervisory control	[12]	571
3	Effects of imperfect automation on decision making in a simulated command and control task	[13]	340
4	Detection of Driver Fatigue Caused by Sleep Deprivation	[14]	169
5	A comparison of two scoring procedures with the NASA task load index in a simulated flight task	[15]	166
6	System of systems integration: Key considerations and challenges	[16]	138
7	Systems integration: Key perspectives, experiences, and challenges	[17]	118
8	Aircraft Simulators and Pilot Training	[18]	108
9	Manual Control Cybernetics: State-of-the-Art and Current Trends	[19]	99
10	Tongue-Movement Communication and Control Concept for Hands-Free Human–Machine Interfaces	[20]	83
11	A methodology of human factors analysis for systems engineering: Theory and applications	[21]	81
12	Human-automation teams and adaptable control for future air traffic management	[22]	80
13	Human systems integration in remotely piloted aircraft operations	[23]	66
14	Human-centered design of complex systems: An experience-based approach	[24]	64
15	Predictive mental workload modeling for semiautonomous system design: Implications for systems of systems	[25]	64
16	Incorporating Human Factor Considerations in Unmanned Aerial Vehicle Routing	[26]	57
17	Complex adaptive systems engineering (CASE)	[27]	56
18	Flight decks and free flight: Where are the system boundaries?	[28]	55
19	Stages and levels of automation in support of space teleoperations	[29]	54
20	A socio-technical analysis of functional properties in a joint cognitive system: a case study in an aircraft cockpit	[30]	51

3.1.1 Authors' publications

Figure 4 shows the number of publications by the 20 authors who produced the most on Human Systems Integration and correlated themes, including the total citations for their publications.

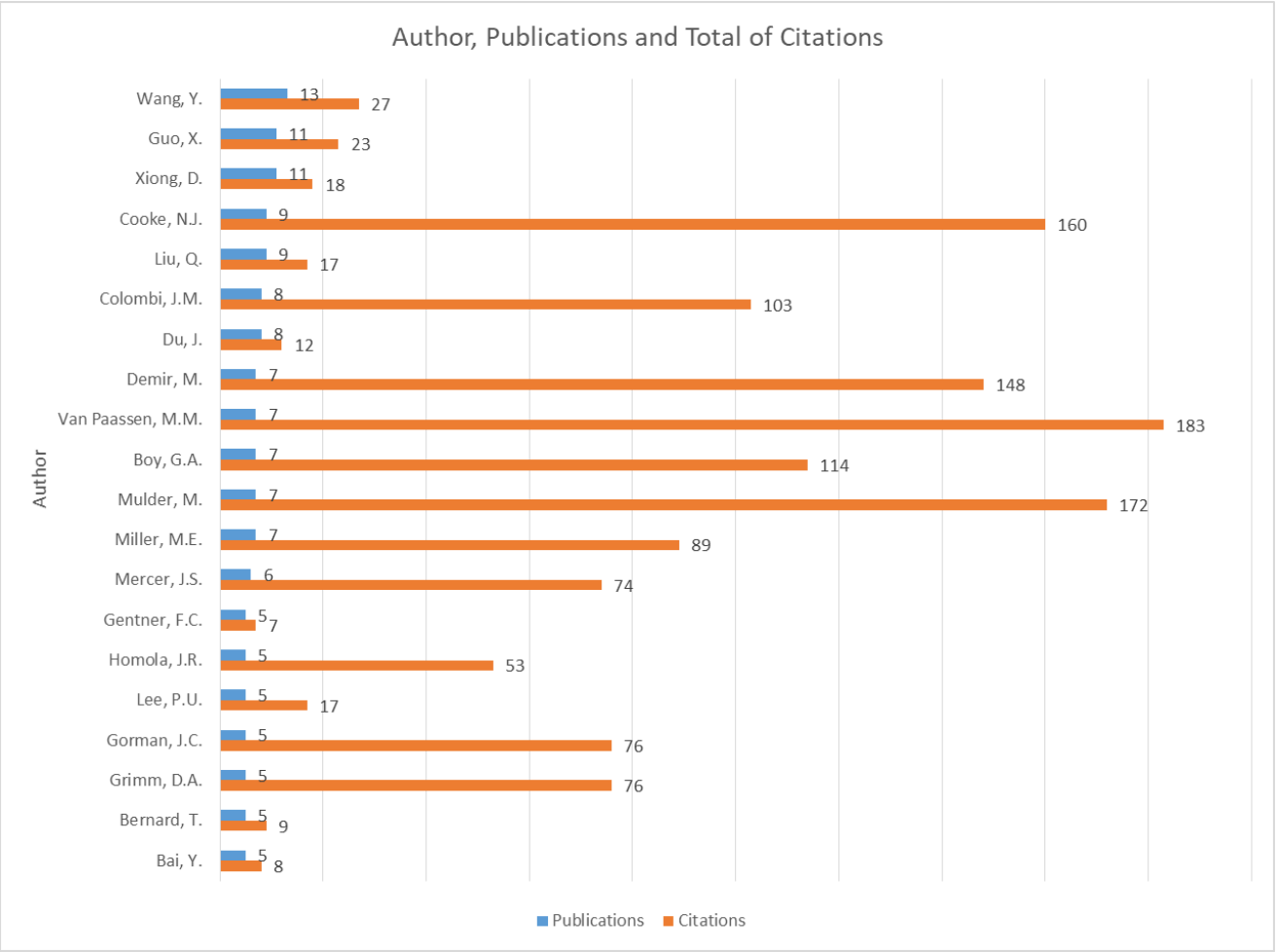

Figure 4 – Authors' productivity and total of citations – HSI and correlates

3.1.2 Main Scientific Journals

In the context of the research algorithm, zoning was carried out according to Bradford's Law, dividing the number of articles into 3 zones. The core zone presented 12 journals, as shown in Table 4, with a frequency of 120 publications.

Table 4 – Main periodicals elected to the core zone, according to Bradford's Law

Order	Source	Frequency	Accumulated Frequency	Country
1	Advances in Intelligent Systems and Computing	23	23	Germany
2	Proceedings of the Human Factors and Ergonomics Society Annual Meeting	18	41	United States
3	Lecture Notes in Electrical Engineering	18	59	Germany
4	IEEE/AIAA Digital Avionics Systems Conference. Proceedings	15	70	United States
5	SAE Technical Papers	10	80	United States
6	Lecture Notes in Computer Science	6	86	Germany
7	AIAA Scitech Forum	6	92	United States
8	Proceedings of SPIE - The International Society for Optical Engineering	6	98	United States
9	Human Factors	6	104	United States
10	Lecture Notes in Networks and Systems	4	108	Switzerland
11	Systems Engineering	4	112	United States
12	IEEE Transactions on Human-Machine Systems	4	120	United States

These journals mentioned in Table 4 represented 33.99% of publications and 6.31% of sources. The other zones represent 37.38% and 56.31% of the sources, with the same productivity. The results demonstrate the greater frequency of publications on Human Systems Integration and correlated themes in a concentrated and smaller set of sources.

3.1.3 Keyword co-occurrence analysis

The keyword co-occurrence analysis was conducted using the Vosviewer 1.6.20 software, which was used for a qualitative and quantitative data network analysis referring to the bibliometric map of keywords.

Using the full counting method for keywords co-occurrence, with a limit of at least 5 keyword appearances, we obtained 171 keywords. We used the presentation method by strength association between keywords, as shown in Figure 5.

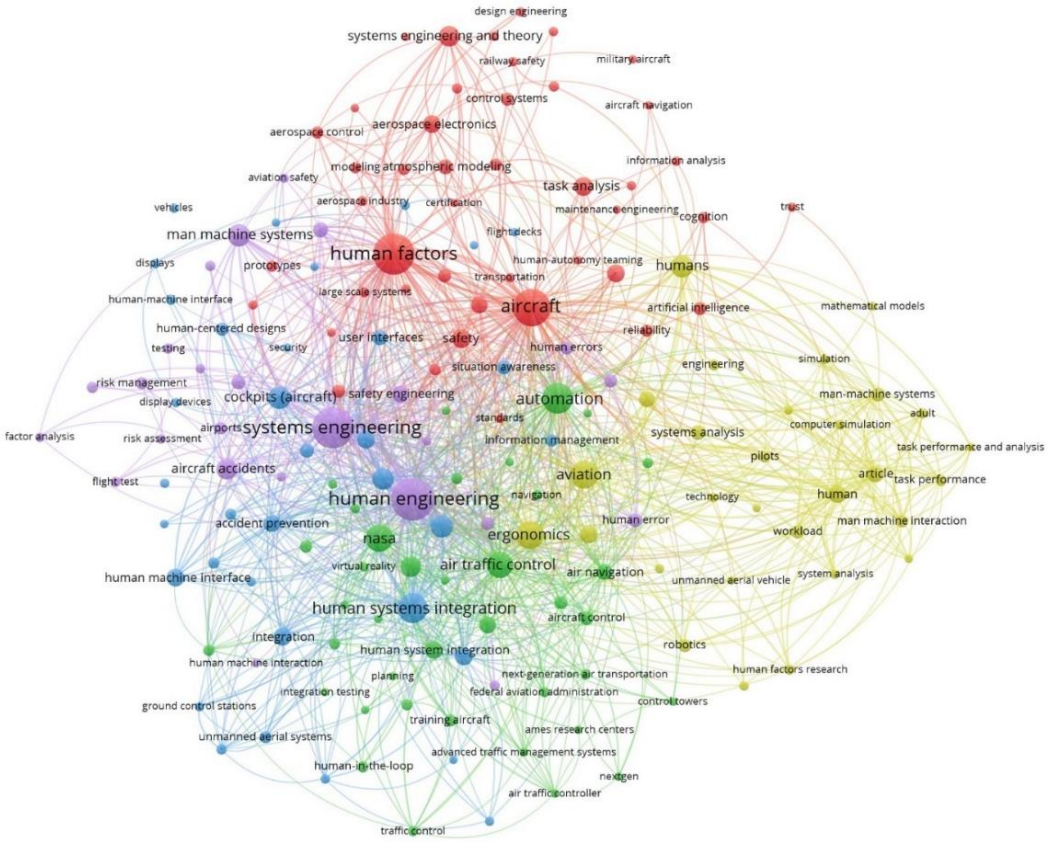

Figure 5 – Keywords co-occurrence – HSI and correlates

The top 20 keywords are presented in Table 5, showing the number of co-occurrences and link strength.

Table 5 – Main Keywords according to the link strength

Order	Keyword	Occurrences	Link Strength
1	Human engineering	96	758
2	Systems engineering	91	595
3	Human factors	88	562
4	Aircraft	74	524
5	Automation	51	379
6	Human systems integration	50	372
7	Aviation	43	371
8	Ergonomics	42	326
9	Air traffic control	39	325
10	Human	19	241
11	NASA	40	235

Order	Keyword	Occurrences	Link Strength
12	Humans	29	231
13	Fighter aircraft	25	228
14	Human-systems integration	28	218
15	Article	16	211
16	Human computer interaction	26	206
17	Aircraft accidents	24	202
18	Unmanned Aerial Vehicles (UAV)	18	201
19	Cockpits (aircraft)	28	197
20	Man machine systems	28	197

It is observed that 4 keywords stand out as being central themes of the research: “Human engineering”, Systems engineering”, “human factors” and “aircraft”. These words are strongly associated with other words that relate to the theme, presenting many connecting lines. Furthermore, they have the largest node sizes, representing more co-occurrences of these keywords.

Five clusters or thematic groups of keywords, divided by color, were also generated, demonstrating a more significant association between these words in each group, as shown in Table 6.

Table 6 – Keywords Clusters

Clusters	Keywords
1 – Aircraft (44 items)	“aerospace control”, “aerospace electronics”, “aerospace engineering”, “aerospace industry”, “aircraft”, “aircraft navigation”, “analytical models”, “artificial intelligence”, “atmospheric modeling”, “avionics”, “certification”, “cognition”, “conferences”, “control systems”, “decision making”, “design engineering”, “digital avionics”, “engineers”, “hazards”, “human factors”, “human-autonomy teaming”, “information analysis”, “instruments”, “laboratories”, “large scale systems”, “maintenance engineering”, “military aircraft”, “modeling”, “monitoring”, “personnel”, “prototypes”, “railway safety”, “reliability”, “reliability analysis”, “safety”, “space technology”, “space vehicles”, “standards”, “system performance”, “systems engineering and training”, “task analysis”, “training”, “transportation”, “trust”
2 – Air Transportation Systems (38 items)	“advanced traffic management”, “air navigation”, “air traffic control”, “air traffic controller”, “air traffic management”, “air transportation”, “aircraft control”, “ames research centers”, “automation”, “control towers”, “decision support systems”, “federal aviation administration”, “fighter aircraft”, “flight control systems”, “flight simulators”, “hardware”, “human system integration”, “human-in-the loop”, “human-systems”, “information technology”, “integration testing”, “legacy systems”, “life cycle”, “manned space flight”, “nasa”, “navigation”, “next-generation air transportation systems”, “nextgen”, “personnel training”, “planning”, “research and development”, “space flight”, “system of systems”, “system requirements”, “technology transfer”, “traffic control”, “training aircraft”, “virtual reality”
3 – Human Systems Integration (35 items)	“accident prevention”, “antennas”, “cockpits (aircraft)”, “design”, “detect and avoid”, “display devices”, “displays”, “flight deck”, “flight decks”, “ground control stations”, “human computer interaction”, “human factors engineering”, “human machine interface”, “human systems integration”, “human-centered design”, “human-machine interface”, “human-systems integration”, “information management”, “integration”, “national airspace system”, “product design”, “robots”, “rock mechanics”, “security”, “situation awareness”, “software”, “system integration”, “unmanned aerial systems”, “unmanned aerial vehicles (uav)”, “unmanned aircraft system”, “user centered design”, “user interfaces”, “vehicles”, “visualization”
4 – Human Performance in aviation (29 items)	“adult”, “airplane pilot”, “article”, “aviation”, “cognitive engineering”, “cognitive systems”, “computer simulation”, “engineering”, “ergonomics”, “human”, “human experiment”, “human factors research”, “humans”, “man machine interaction”, “man-machine systems”, “mathematical models”, “pilots”, “real time systems”, “remotely piloted aircraft”, “robotics”, “simulation”, “system analysis”, “systems integration”, “task performance”, “task performance and analysis”, “technology”, “unmanned aerial vehicle”, “workload”
5 – Human Engineering & Safety (25 items)	“accidents”, “aircraft accidents”, “airports”, “aviation safety”, “civil aviation”, “errors”, “factor analysis”, “flight dynamics”, “flight test”, “general aviation”, “human engineering”, “human error”, “human errors”, “human machine interaction”, “human performance”, “human resource management”, “job analysis”, “man machine systems”, “performance”, “risk assessment”, “risk management”, “safety engineering”, “software testing”, “systems engineering”, “testing”

Along with the keywords co-occurrence map, a visualization of this map was also generated using year overlay visualization (Figure 6) to map research trends concerning Human Systems Integration and correlated themes over the years.

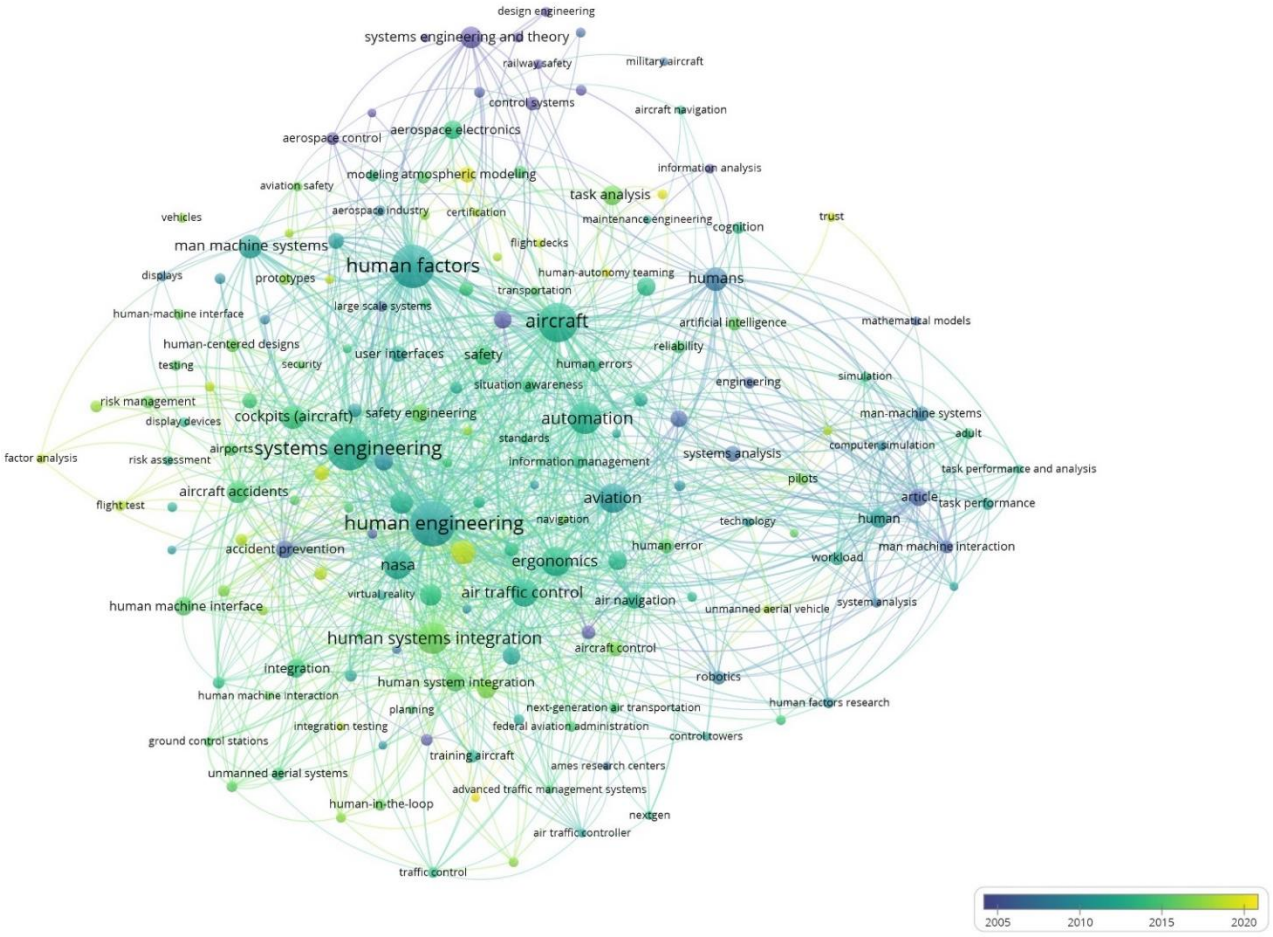

Figure 6 – Keywords co-occurrence by year overlay visualization - HSI and correlates

Figure 6 confirms that scientific production between 2005 and 2015 was quite evident. It highlights that the central keywords — human engineering, systems engineering, human factors, and aircraft — were also very present in this research period. Keywords such as “systems engineering and theory” are more relevant for a context before 2005, demonstrating that this integration with the concepts of human factors has evolved over the decades.

For example, keywords such as “human systems integration”, which also has the function of integrating the concepts of human factors and systems engineering, are already more relevant in the period after 2015 and evolving at the beginning of the 2020s, also occurring more significant connections with concepts of increasingly automated systems, such as “advanced traffic management systems”, “unmanned aerial vehicle”, “flight decks” and “human-centered design”.

3.2 AI Systems

According to the research algorithm, 452 results from the compiled database were analyzed for AI Systems. Figure 7 presents a graph showing the annual evolution of publications on this topic and the total number of citations per year.

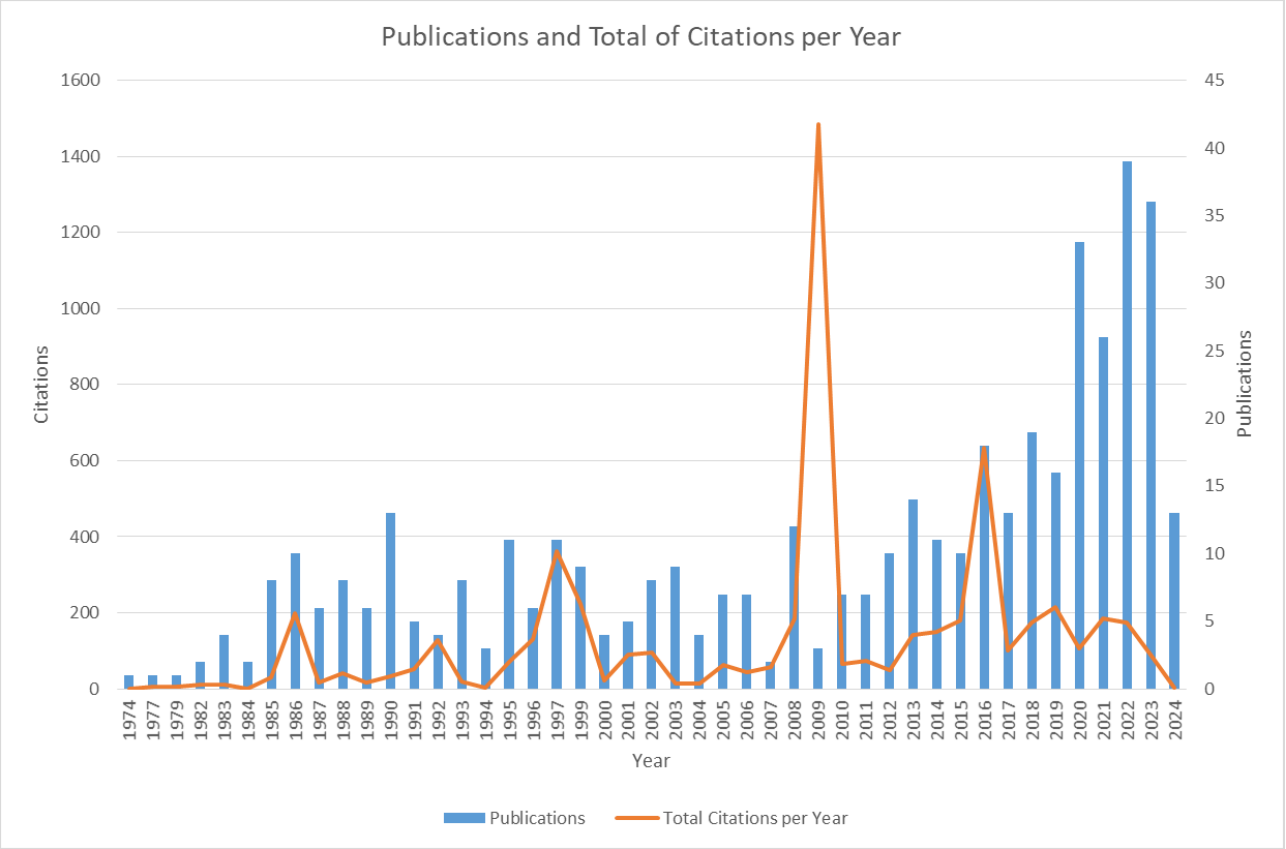

Figure 7 – Publications and total of citations per year (AI systems)

Figure 7 shows that there has been an increasing number of publications on the topic in recent years, with a peak between 2022 and 2023, in addition to a tendency for research to continue at high numbers.

The most prominent peak in citations occurred in 2009 (1484 citations), with the relevant contribution by Banich [34] on the context of executive function in general, but which is closely related to the concepts of Human-AI teaming. Another vital year of contributions occurred in 2016 (633 citations), with publications by Nanduri & Sherry on data anomaly detection in aircraft using Recurrent Neural Network (RNN) [36]; Liu et al. and Stanton, Harris & Starr, with publications on the future of the flight deck and the human-machine interface for single pilot operations [38, 39].

Despite the lower average number of citations in recent years, an average pattern of approximately 140 citations is observed, which is relevant considering the recent evolution of topics that specifically address systems based on artificial intelligence. Table 7 presents the most cited articles for this research topic.

Table 7 – Most cited articles for AI Systems in aviation

Order	Title	Ref.	Citations
1	Executive function: The search for an integrated account	[34]	1479
2	Prototype conflict alerting system for free flight	[35]	250
3	Anomaly detection in aircraft data using Recurrent Neural Networks (RNN)	[36]	224
4	A Review of Situation Awareness Assessment Approaches in Aviation Environments	[37]	129
5	Cognitive pilot-aircraft interface for single-pilot operations	[38]	119
6	The future flight deck: Modelling dual, single and distributed crewing options	[39]	103
7	Evaluating two aspects of direct manipulation in advanced cockpits	[40]	102
8	Cognitive networks as a guide to menu organization: An application in the automated cockpit	[41]	99
9	Rotorcraft Pilot's Associate: Design and evaluation of an intelligent user interface for cockpit information management	[42]	83
10	Multimodal Intelligent Eye-Gaze Tracking System	[43]	79
11	ATOMS: Air Traffic Operations and Management Simulator	[44]	75
12	User involvement in the early stages of the development of an aircraft warning system	[45]	72
13	Comparing the performance of expert user heuristics and an integer linear program in aircraft carrier deck operations	[46]	62
14	CogEmoNet: A Cognitive-Feature-Augmented Driver Emotion Recognition Model for Smart Cockpit	[47]	53
15	Quantifying cognitive workload in simulated flight using passive, dry EEG measurements	[48]	49
16	Perceived clutter in advanced cockpit displays: Measurement and modeling with experienced pilots	[49]	48
17	Development and evaluation of a cockpit decision-aid for emergency trajectory generation	[50]	47
18	Fatigue Detection in Commercial Flight Operations: Results Using Physiological Measures	[51]	47
19	Multidimensional measure of display clutter and pilot performance for advanced head-up display	[52]	47
20	Visual scanning strategies in the cockpit are modulated by pilots' expertise: A flight simulator study	[53]	46

3.2.1 Authors' Publications

Figure 8 shows the number of publications by the 20 authors who produced the most on AI Systems in aviation and the total citations for their publications.

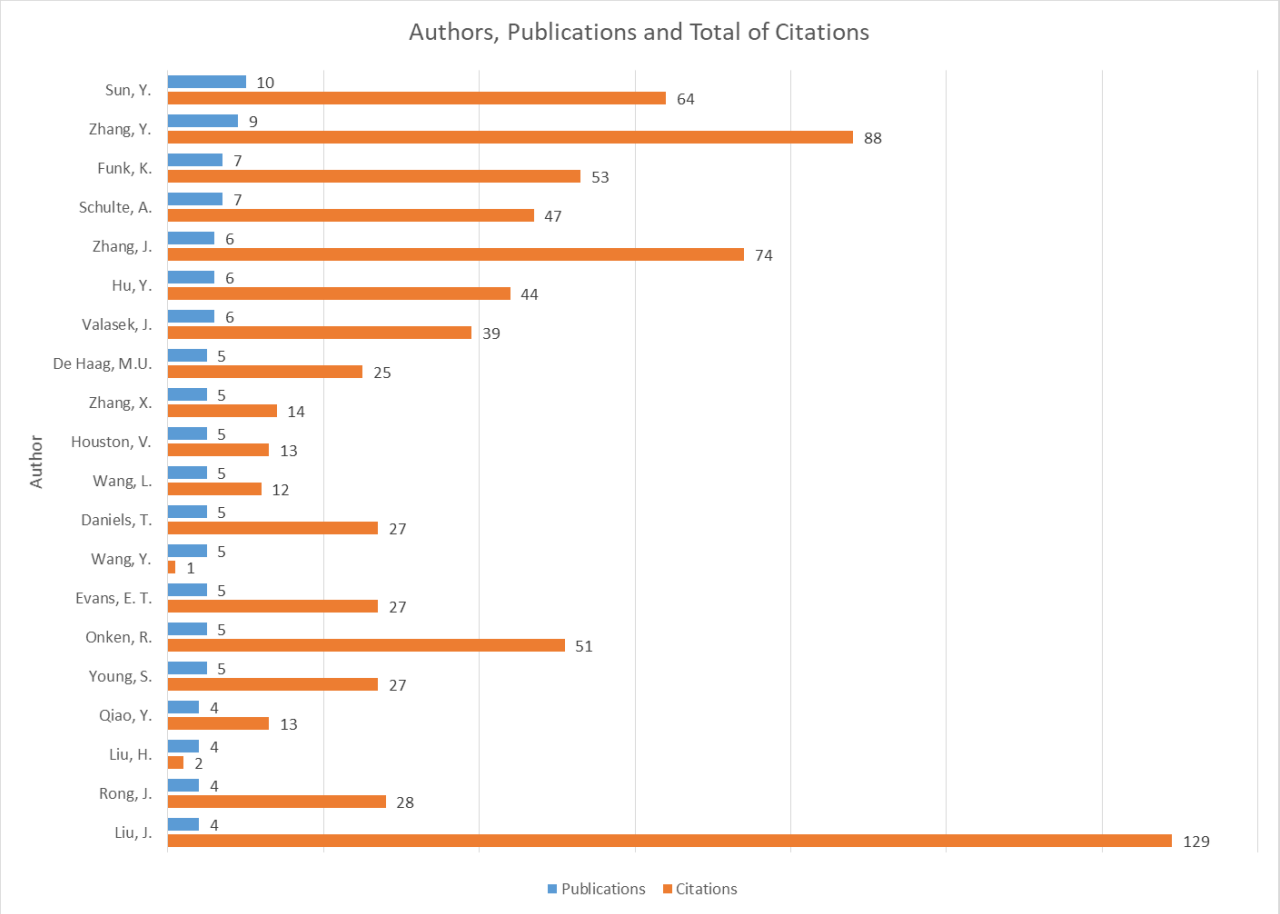

Figure 8 – Authors' productivity and total of citations – AI Systems in aviation

3.2.2 Main Scientific Journals

In the context of the research algorithm, zoning was carried out according to Bradford's Law, dividing the articles into 3 journal zones. The core zone that dealt with AI Systems in aviation presented 14 journals, as shown in Table 8, with a frequency of 152 publications.

Table 8 – Main periodicals elected to the core zone, according to Bradford's Law

Order	Source	Frequency	Accumulated Frequency	Country
1	IEEE/AIAA Digital Avionics Systems Conference Proceedings	32	32	United States
2	National Aerospace and Electronics Conference, Proceedings of the IEEE	20	52	United States
3	Proceedings of SPIE - The International Society for Optical Engineering	15	67	United States
4	Proceedings of the IEEE International Conference on Systems, Man and Cybernetics	15	82	United States
5	Lecture Notes in Computer Science	13	95	Germany
6	Advances in Intelligent Systems and Computing	9	104	Germany
7	Journal of Physics: Conference Series	8	112	United Kingdom
8	SAE Technical Papers	8	120	United States
9	Annual Forum Proceedings - American Helicopter Society	7	126	United States
10	Aerospace America	6	131	United States
11	IEEE Access	5	136	United States

Order	Source	Frequency	Accumulated Frequency	Country
12	IEEE Aerospace and Electronic Systems Magazine	5	141	United States
13	ACM International Conference Proceeding Series	5	145	United States
14	Lecture Notes in Electrical Engineering	4	152	Germany

These journals mentioned in Table 8 represented 33.63% of publications and 5.34% of sources. The other zones represent 38.55% and 56.11% of the sources, with the same productivity. Thus, the results also demonstrate the greater frequency of publications on AI Systems in Aviation in this concentrated set of journals.

3.2.3 Keywords Co-occurrence Analysis

201 keywords were obtained using the full counting method for keyword co-occurrence, with a limit of at least 5 keyword appearances. We used the presentation method by strength association between keywords, as shown in Figure 9.

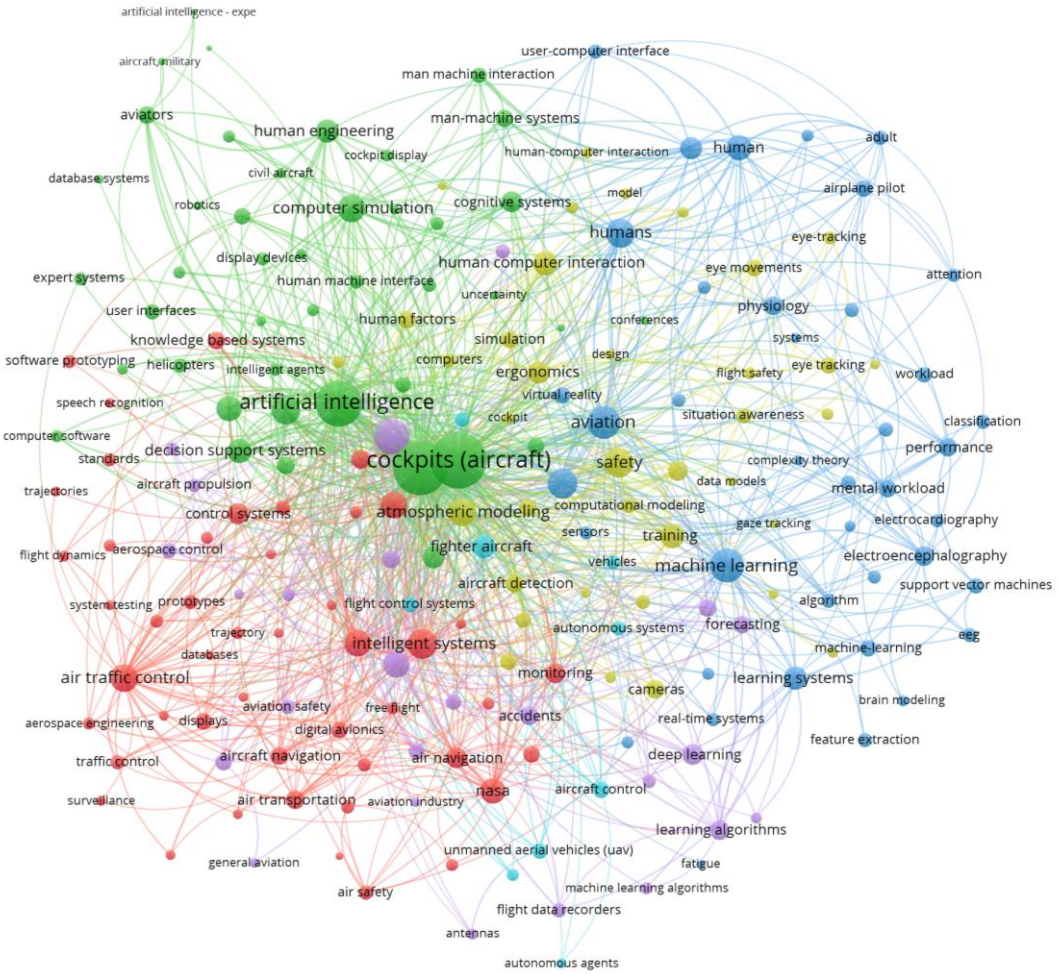

Figure 9 – Keywords co-occurrence – AI Systems in aviation

The top 20 keywords are presented in Table 9, which also shows the number of occurrences and link strength.

Table 9 – Main Keywords according to the link strength

Order	Keyword	Occurences	Link Strength
1	Cockpits (aircraft)	134	815
2	Aircraft	123	771
3	Artificial Intelligence	94	556
4	Automation	47	335
5	Machine learning	38	315
6	Aviation	39	296
7	Safety	35	253
8	Flight simulators	36	248
9	Intelligent systems	45	240
10	Decision making	37	237
11	Humans	21	223
12	Air traffic control	30	214
13	Computer simulation	25	210
14	Atmospheric modeling	30	206
15	Aerospace electronics	30	197
16	Aircraft accidents	27	194
17	Flight decks	27	194
18	NASA	25	188
19	Human	15	184
20	Avionics	28	179

It is observed that, in this case, the keywords “cockpits (aircraft)”, “aircraft” and “artificial intelligence” have a great strength of association with other words that connect with the theme of AI systems in aviation, presenting a large number of lines of connection. Furthermore, they also have the largest node sizes compared to other keywords, representing a more significant number of occurrences of these keywords.

From the analysis, 6 clusters of keywords were processed and divided by color, which demonstrates a more significant association between these words in each group, as shown in Table 10. These clusters were named by thematic groups that best defined the set of keywords.

Table 10 – Keywords Clusters

Clusters	Keywords
1 – Intelligent Systems (47 items)	“aerospace electronics”, “aerospace engineering”, “aerospace safety”, “aerospace simulation”, “air navigation”, “air safety”, “air traffic control”, “air transportation”, “aircraft instruments”, “aircraft navigation”, “airplanes”, “airports”, “autonomy”, “computer architecture”, “computer vision”, “control systems”, “costs”, “databases”, “digital avionics”, “displays”, “flight decks”, “flight dynamics”, “free flight”, “information systems”, “intelligent systems”, “knowledge based systems”, “machine vision”, “mathematical models”, “meteorological radar”, “military aircraft”, “military computing”, “monitoring”, “monte carlo methods”, “nasa”, “navigation”, “pattern recognition”, “prototypes”, “reliability”, “software prototyping”, “speech recognition”, “standards”, “surveillance”, “system testing”, “traffic control”, “trajectories”, “trajectory”, “weapons”
2 – Aircraft & AI (43 items)	“aircraft”, “aircraft – cockpits”, “aircraft communication”, “aircraft, military”, “alarm systems”, “algorithms”, “artificial intelligence”, “artificial intelligence – expert systems”, “aviators”, “avionics”, “civil aircraft”, “cockpit display”, “cockpits (aircraft)”, “cognitive systems”, “computer simulation”, “computer software”, “conferences”, “database systems”, “decision making”, “decision support systems”, “display devices”, “expert systems”, “flight deck”, “helicopters”, “human engineering”, “human machine interface”, “information management”, “intelligent agents”, “intelligent control”, “intelligent robots”, “man machine interaction”, “man machine systems”, “man-machine systems”, “military helicopters”, “optimization”, “real time systems”, “resource management”, “robotics”, “situational awareness”, “technology”, “three dimensional computer graphics”, “uncertainty”, “user interfaces”

Clusters	Keywords
3 – Pilot Monitoring (40 items)	“adult”, “airplane pilot”, “algorithm”, “article”, “attention”, “aviation”, “biomedical monitoring”, “brain modeling”, “classification”, “cognition”, “complexity theory”, “decision trees”, “eeg”, “electrocardiography”, “electroencephalography”, “fatigue”, “feature extraction”, “flight simulation”, “flight simulators”, “human”, “humans”, “learning systems”, “machine learning”, “machine-learning”, “mental workload”, “performance”, “physiological models”, physiology”, “pilots”, “predictive models”, “psychology”, “real-time systems”, “sensors”, “signal detection”, “support vector machines”, “systems”, “user-computer interface”, “virtual reality”, “visual perception”, “workload”
4 – Human Factors engineering (37 items)	“aircraft cockpit”, “aircraft detection”, “analytical models”, “artificial neural network”, “atmospheric modeling”, “cameras”, “cockpit”, “computational modeling”, “computers”, “data models”, “design”, “ergonomics”, “eye movements”, “eye tracking”, “eye-tracking”, “flight safety”, “gaze tracking”, “gesture recognition”, “human computer interaction”, “human factors”, “human-computer interaction”, “image processing”, “instruments”, “intelligent vehicle highway systems”, “job analysis”, “model”, “modeling”, “performance evaluation”, “pilot”, “process control”, “safety”, “simulation”, “situation awareness”, “task analysis”, “training”, “transportation”, “visualization”
5 – AI Systems Design (25 items)	“accident prevention”, “accidents”, “aerospace control”, “aircraft accidents”, “aircraft manufacture”, “aircraft propulsion”, “antennas”, “automation”, “aviation industry”, “aviation safety”, “civil aviation”, “convolutional neural networks”, “deep learning”, “engines”, “errors”, “flight crews”, “flight data recorders”, “forecasting”, “general aviation”, “learning algorithms”, “machine learning algorithms”, “neural networks”, “object detection”, “pilot operations”, “training aircraft”
6 – Autonomous Systems Integration (9 items)	“aircraft control”, “autonomous agents”, “autonomous systems”, “fighter aircraft”, “flight control systems”, “integration”, “national airspace system”, “unmanned aerial vehicles”, “vehicles”

Along with the word co-occurrence map, a visualization of this map was also generated using year overlay visualization (Figure 10).

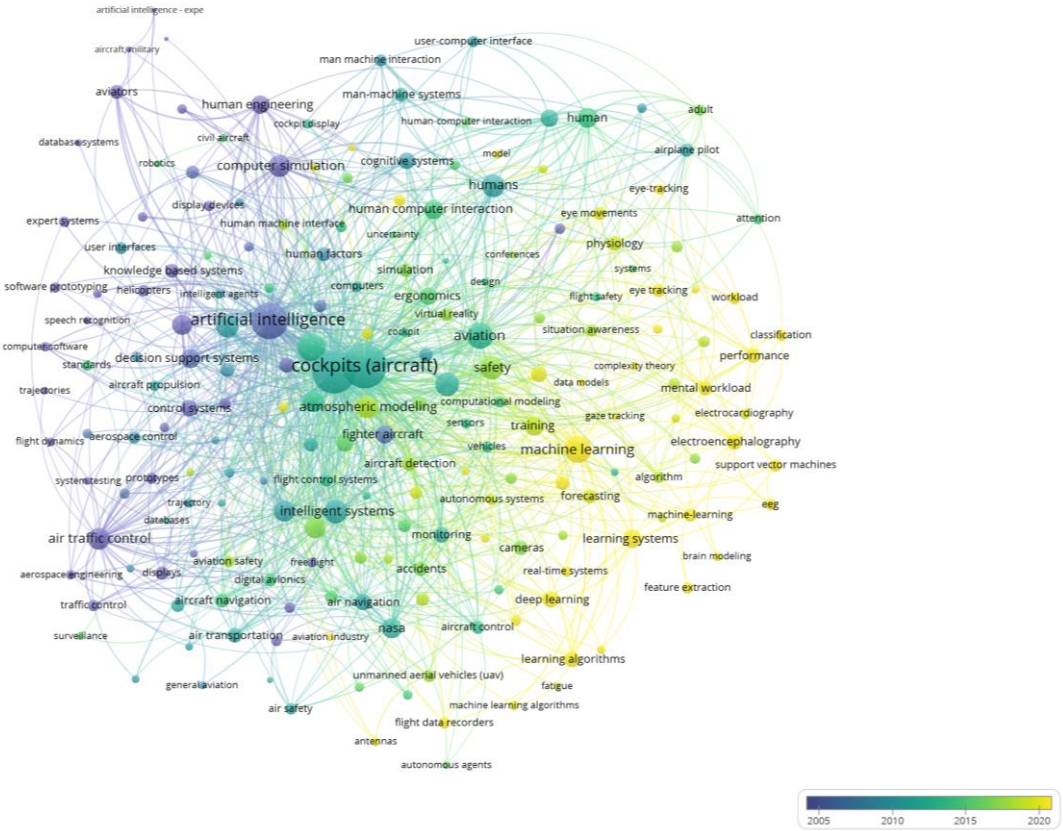

Figure 10 – Keywords co-occurrence by year overlay visualization – AI Systems

This second analysis shows a more apparent division of research themes over the years. Research from the early 2000s and previous ones has already dealt with artificial intelligence, which has an important connection to knowledge-based systems (KBSs), computer simulation, and air traffic control.

There is a constant evolution regarding the study of these systems for aircraft, which is demonstrated by the relationship of the central keyword “cockpits (aircraft)” with themes that are becoming increasingly integrated, such as “intelligent systems”, “autonomous systems” and “human-computer interaction”.

It is also noteworthy that many initial studies begin not only in the aeronautical sector but also come from the space and defense sectors, with significant contributions from “NASA” in developing intelligent systems and perspectives for Human Systems Integration.

Since 2015, there has been significant growth in studies related to AI systems. Research on “Machine Learning” and “Deep Learning” stands out. These are relevant keywords in the current context and are the basis for developing AI systems that can be applied not only on the flight deck but in aviation in general.

3.3 Content Analysis

In the research context, it is important to record some concepts from the literature review to understand how these themes have evolved until we reach the current context of AI systems design.

In addition to including AI in aviation, the entire aviation industry is developed through processes and methods that aim to integrate the complex systems that encompass the development of the aeronautical product. This multidisciplinary and holistic approach includes Systems Engineering (SE), which is the art and science of developing an operational system capable of meeting defined requirements within constraints often conflicting. As an integrative discipline, several systems are evaluated and balanced with each other to produce a coherent whole that is not dominated by the perspective of a single system [5].

Systems Engineering is the foundation for the architecture of a complex system such as an aircraft, ensuring coverage of the entire product life cycle.

> “SE allows one to better understand each product as a whole and to improve the planning, design/development, manufacturing, and maintenance processes. Organizations use SE to model and analyze the interactions, needs, subsystems, constraints, and interactions among system components and to optimize and trade off important decisions throughout the product lifecycle (…). Systems engineers use a variety of modeling techniques and tools to capture, organize, prioritize, deliver, and manage system information throughout an entire product lifecycle [6]”.

One of the stages of Systems Engineering processes involves analyzing and integrating the development of systems with user needs. NPR 7123.1 states that:

> “The systems approach is applied to all elements of a system (i.e., hardware, software, human systems integration). In short, the systems engineering approach must equally address and integrate these three key elements: hardware, software, and human systems integration. Therefore, the human element is something that integration and systems engineering processes must address [7]”.

Based on that, since the first wave of AI, which comprised technologies embedded in aviation that had a high level of automation, the discipline of Systems Engineering has remained at the forefront of implementing these technologies. Systems Engineering has predominantly led in producing cost-effective, reliable, and safe aviation systems. Likewise, Systems Engineering will need to evolve and be applied throughout the entire life cycle of AI-controlled aviation systems [2].

The AI-controlled aviation systems are increasingly considered part of a collaborative team with the end user, in this case, the pilots.

Human-machine teaming (HMT), also called human-AI teaming (HAT), typically combines perspectives from systems engineering, artificial intelligence, and human-centered design to achieve human systems integration (HSI) through the development of an integrative systems representation that encapsulates human and machine attributes and properties [54]. Guy A. Boy also proposes that:

> "The combination of human and machine autonomy, where machine autonomy is the capacity of a machine to act safely and efficiently on its own in an environment, and human autonomy refers to people solving problems, often unexpected, using appropriate human skills and knowledge, as well as technological and organizational support.
>
> This interface must be precisely defined in aviation. While automation has proven to be a useful and essential solution to safety in well-specified contexts, it makes work processes more rigid, often counterproductive, or even dangerous, specifically in unexpected situations in which flexibility is needed to perform problem-solving tasks. Specifically, how can technology, organizations and people's competence improve this flexible problem-solving in unexpected situations?" [54]

EASA also brings these issues to light, addressing the need for scientific development to fill these gaps. This is supported by the need to ensure that the implementation of AI Systems remains safe and can evolve into even more evolved human-AI teaming.

Various challenges for introducing AI systems in aviation have been identified and must be addressed when developing this technology. Some of these challenges correlate with the objective of this paper, including [1]:

- "Adapting assurance frameworks to cover the specificities of identified AI techniques and address development errors in AI-based systems and their constituents;
- With the evolution of AI-based systems, there is a need for guidance on how to introduce and effectively use the Human-AI teaming. This involves in particular the challenges of the shared understanding of goals and decision-making processes between the human and AI-based systems.
- Elaborate pertinent guarantees on stability and robustness of AI models and on the absence of "unintended behavior" in AI applications."

3.3.1 AI Systems

Based on the analysis of extracted data, continuous flight deck automation has been discussed for many decades in aviation. Concepts have evolved, starting from rigid automation to AI-based automation.

In the 1980s, as we can analyze from the data extracted, the concern with addressing aspects of human factors in new generations of cockpits was essential for the development of new technologies on the flight deck, such as multifunction displays that began to replace electro-mechanical instruments [55], in addition to the inclusion of computer-controlled subsystems that increased the complexity of integration [56].

The mention of AI had also already occurred, so this was one of the models that could contribute to integrating onboard automation and other elements, such as voice commands and new-generation displays [57, 58].

Mainly from the 80s onwards in aviation, the first AI concepts began to be treated in articles mainly from the point of view of Expert Systems (ES), which are systems designed to simulate the problem-solving behavior of a person who would be an expert in that specific domain [59].

From the perspective of identifying what the design of the next generations of flight decks would be like, some articles sought to discuss interface components that would be implemented, such as heuristic voice, a greater number of displays, and holographic systems, considering that flight deck systems would also be capable of monitoring and act according to the pilot's mental and physiological state [60]. Other technologies mentioned in this decade brought to light tools that could be essential for the pilot in automatically planning navigation and routes and evaluating and reacting to risks [61].

Therefore, due to the implementation of new digital technologies on the flight deck, there was a concern that human-machine interaction could be mainly favorable to the aircraft, and the pilot, the intelligent part of the interface, could be neglected. Implementing new designs should always ensure that the pilot can override any decision-making to be carried out by automation. Furthermore, the aeronautical industry's quest was to provide confirmed gains in safety and operational efficiency [55].

However, there is also a growing understanding that new developments in avionics technologies must involve great integration in the most diverse sectors of aviation, from technology engineering to the pilot, through air traffic control to artificial intelligence techniques [61]. Although aeronautical development has always been guided by the continuous improvement and evolution of the flight deck for pilots, human systems integration has become imperative as a discipline and part of systems engineering, covering everything from design to validation of aspects of human factors.

We can understand this as a concern that followed and will reach current discussions on implementing more robust Artificial Intelligence systems.

From the 90s onwards, Expert Systems and Knowledge-Based Systems continued to be studied, and complementary studies regarding the performance and workload of pilots using these new avionics systems were also published [62, 63, 64, 65].

Studies on human-machine interaction were also carried out, focusing on communication between the pilot and an intelligent Fault Management System [66].

Also, some studies focused on how the transition from an automatic to a manual system would occur, highlighting the importance of a smooth transition [67].

This transition of technologies occurs in an evident sense: the pilot stops being an aircraft controller and becomes a systems' manager, mainly due to the increase in the number of avionics systems and their complexity. To do this, he becomes responsible for Cockpit Task Management (CTM), which will include starting a task, prioritizing it, executing it, and finishing it [68].

In some cases, systems such as Rotorcraft Pilots' Associates (RPAs) brought the concept of assistance to the pilot as a third crew member in the sense of managing situations on the flight deck [69, 70].

Still, during this period, important discussions were brought to light regarding the increasingly early integration of the expertise of the end user in the design process of new automated systems. Although this concept gives us the idea that this is, in fact, essential and ideal for the design of a system, in practice, there are several difficulties in integrating the engineer responsible for the design and the end user, who, in this case, would be the pilots [71]. Systems engineering and a human-centered approach must be part of this systems analysis and validation process.

Another important research was the creation of Knowledge-Based Systems that facilitated the management of activities on the flight deck. These systems incorporated artificial intelligence concepts and used research on human factors in their design [72].

In the 2000s, some articles investigated and proposed that AI proved to be better suited to Flight management and supporting pilots' decision-making than aircraft control [73].

It is also observed that implementing new intelligent systems mainly seeks to assist the pilot in approaching and landing, improving situational awareness, decision-making, and reducing the workload [74].

With the integration of tools to support tasks in the cockpit, the integration of these intelligent systems with Flight Safety and Risk Management initiatives for operators and airlines is also essential [75], as company management is also part of the vision of the whole of Human Systems Integration.

From 2015 onwards, we found the first topics related to machine learning, such as the development of specific avionics systems.

During this period, several articles also addressed the requirements and questions regarding single-pilot operations (SPO), a theme that can receive contributions from AI systems. How to deal with the workload of just one pilot? How to override co-pilot actions? What are the ethical implications and public acceptance of this change? What safety mechanisms will the aircraft need to allow only one pilot on board? [76, 77, 81, 82].

The concern is consolidated with discussions about Increasingly Autonomous Systems (IAS), where these systems can only be implemented and certified when they work in full concert with the human agent, formulating trust between the two and establishing an atmosphere of team contribution. Through this research, it has already been observed that task performance is significantly higher when the pilot and the IAS are combined than when the IAS works individually or just the pilot executes actions individually, without the help of the intelligent system [78, 79].

As of 2020, there has been a considerable increase in research based on the proposed methodology, which corroborates the transition between the previous automation of the flight deck and the proposals for new intelligent systems with AI as a central concept.

4 Discussions and Conclusions

Considering the articles researched in AI Systems, it is observed that their application and development on the flight deck still depend on several processes, mainly related to the certification of those systems. The vast majority of research involving intelligent systems has been carried out in recent years. These intelligent systems are more complex and integrated than the Expert Systems and Knowledge-Based Systems developed in previous decades.

From this, it is noted that main research fronts are advancing with a greater volume of publications and development. These themes are presented in Table 11.

Table 11 – Core Themes for AI Systems Research

Core Theme	Quantity of Publications
Machine Learning (ML) solutions	45
Deep Learning (DL) solutions	21
AI-based systems for eye-tracking and pilots' movements analysis	19
AI-based systems for assistance in Single Pilot Operations	17

It is noted that the development of AI Systems that are directly applied to the flight deck will still need to involve varied discussions with different stakeholders in the aviation industry who can contribute to the certification process of these systems. From a Human Systems Integration point of view, pilots must be involved in the initial phases of Preliminary Design Reviews (PDRs) and participate in the entire design process of how the interaction with the AI System will occur. This participation is essential so that the pilot is familiar with the AI System and that the system can be an assistant in flight, either automatically monitoring the pilot's cognitive performance or participating more actively in some operation.

Possibilities are noted for advancing these human factors validation systems in training simulators, with AI systems on the flight deck that can monitor mental fatigue or pilot actions through deep learning and learning patterns that the pilot executes. More specifically, concerning flight operations, possible studies that can combine knowledge of standards adopted in flight manuals, such as the Standard Operating Procedures Manual (also known as SOP manual), can contribute to AI flight assistant systems that act as a verifier of the standardized actions adopted for Crew Resource Management (CRM).

Finally, in addition to these significant topics that have been researched from the point of view of AI Systems, and although there are studies related to deep learning solutions, studies related to the application of Generative AI on the flight deck are still incipient. It is a new path of research that can benefit the flight crew, initially as a training device, and which will also depend on robust safety standards for the automatic learning of this specific type of AI system.

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