

Bibliometric Mapping of Human-Machine Interfaces in Autonomous and Intelligent Systems

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The growing integration of autonomous systems in industry has reinforced the demand for efficient Human-Machine Interfaces (HMIs) to ensure safe and adaptive interactions. This study presents a bibliometric analysis of 99 publications (2015–2025) on supervisory interfaces, using Scopus data and tools such as VOSviewer and Bibliometrix. The results revealed six main clusters, centered on terms like human-machine interface, process control, machine learning, and decision-making. The analysis highlights the leadership of China, the United States, and India, while showing the absence of Brazilian contributions. A marked rise in publications occurred after the COVID-19 pandemic, although gaps persist in applied studies involving biosystems.

Keywords: Bibliometric Analysis. Combined Technologies. HMI. Process Control.

Abbreviations: HMI, Human-Machine Interface. SCADA, Supervisory Control and Data Acquisition. AI, Artificial Intelligence. PLC, Programmable Logic Controller. Sustainable Development Goals, SDG.

The integration of humans and intelligent machines is a central feature of industrial transformation. In Industry 4.0, automation plays a key role in optimizing processes, reducing human effort, and increasing productivity [1]. Autonomous systems that work independently with the help of mechanical, control, computing, and communication technologies have emerged as a natural development [2].

Despite their potential for efficiency and scalability, these systems still require human supervision through safe, understandable, and reliable interfaces. Human-Machine Interfaces (HMIs) are essential for mediating interactions in automated environments and supporting monitoring, control, and decision-making [3].

Autonomy has gained strategic importance across various sectors, including biotechnology, chemical engineering, and defense. Reports, such as *The Status of Autonomy in the Department of Defense Unmanned Systems*, underscore this importance [4]. However, systematic study of HMI development in autonomous systems remains

scarce, especially after the COVID-19 pandemic, and given the growing interest of industrialized nations. In Brazil, research and investment in this area are still limited [5].

Understanding the evolution of HMI research is key to identifying trends, gaps, and future directions. These insights support the development of safer and more effective interfaces that meet the requirements of Industry 4.0.

This study aims to map and analyze the scientific production on Human-Machine Interfaces (HMIs) in autonomous and intelligent systems between 2015 and 2025, using Scopus data. Through the application VOSviewer and Bibliometrix (via Biblioshiny), it aims to identify thematic trends, international collaboration networks, and under-researched areas, focusing on the positioning and contributions of the Brazilian context within the global scenario.

Materials and Methods

Database Survey

A quantitative and descriptive bibliometric study was carried out to collect data from articles in the Scopus database. The platform was searched using Boolean operators with the following terms: “supervisory interface” OR “HMI” OR “supervisory control system” AND “autonomous

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systems” OR “intelligent systems” OR “smart process”, “bioreactor” OR “biological reactor” OR “process control”, and “data interpretation” OR “data visualization”. Results were filtered by language (English), publication period (2015–2025), document type (articles and reviews), and subject areas (Computer Science, Engineering, and Chemical Engineering). After applying these criteria, 99 documents were selected, and their citation information, bibliographic data, abstracts, and keywords were exported in .csv format for bibliometric analysis.

Bibliometric Tools

After data collection, the .csv file was processed using two different software tools, both designed for bibliometric analysis: VOSviewer and Bibliometrix. The first software used was VOSviewer. It is a free tool for building and visualizing bibliometric networks between user-defined elements [6].

In VOSviewer, the following parameters were set when importing the data: co-occurrence check with full count, including all keywords. A minimum of four occurrences was required for a keyword to be included in the map. The threshold was chosen because three occurrences resulted in too many terms, while five returned too few. Using these parameters, 49 keywords were identified and selected to avoid redundancy on the map. After a visual inspection, 47 keywords were manually selected.

Bibliometrix, on the other hand, is an R-based package that integrates with a web interface called Biblioshiny [7], designed for the analysis of scientific mapping data [8]. To use it, the R programming language and the RStudio IDE were installed. The Bibliometrix library was then loaded, and the .csv data imported. After the setup, Biblioshiny was launched to generate the necessary graphs and maps.

Unlike VOSviewer, the graphical settings in Biblioshiny can be adjusted individually for each visualization and changed during the analysis to

include more or less data. Relevance maps were generated using all keywords, comparing the most frequent terms over 2015–2021 and 2022–2025. Additionally, charts were created to show the top five countries with the highest research output and the number of publications per year.

Results

In order to examine keyword co-occurrence, thematic clusters, temporal trends, and geographic distribution, we used the VOSviewer and Bibliometrix tools to generate maps and graphs. Thus, the data presented below represent a structured interpretation of the evolution of research on human-machine interaction and supervisory interfaces over the last decade, demonstrating a systematic evaluation of the information obtained.

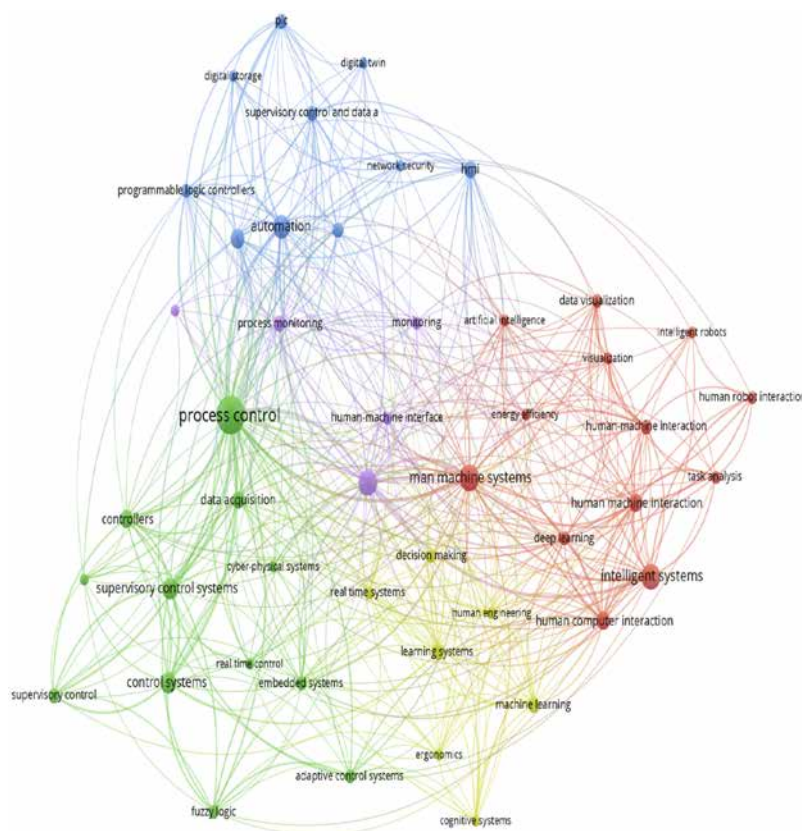
Analysis using VOSviewer

VOSviewer generated a bibliometric map based on articles extracted from the Scopus database, organized by similarity and term frequency (Figure 1). Six main clusters were identified, interconnected by central nodes such as “human-machine interface”, “process control”, “machine learning”, and “decision making”, which structure the main relationships between the topics.

The term “human-machine interface” occupies a central position in the diagram, linked to technical areas such as “SCADA”, “PLC”, and “digital twin”, as well as cognitive aspects such as “learning systems” and “data visualization”. The centrality of the map highlights its role as a link between human cognition and automated systems. Adaptive interfaces tend to improve situational awareness and supervisory performance [9], with multilevel delegation being a promising model in this context [10].

The study suggests that future systems should go beyond data display to act as active agents in decision making, risk anticipation, and contextual adaptation, positioning humans more

Figure 1. VOSviewer bibliometric map showing 5 different clusters separated by colors and their connections with other keywords.



as supervisors rather than operators, mainly in complex environments such as biotechnology and bioprocesses, where real-time interpretation is essential.

The term “process control” is the largest node in the graph, maintaining its relevance despite advances in intelligent systems. It is directly linked to technologies such as “supervisory control systems”, “embedded systems”, and “real-time control”, confirming its technical core role. In biotechnology, its presence reinforces the need for robust and responsive control systems in the face of biological variability and production conditions, paving the way for interfaces that enable more precise control in dynamic bioprocesses.

“Machine learning” appears as a vector of system evolution, linked to terms such as “deep learning”, “learning systems”, and “decision making”. Its peripheral but highly connected position indicates an emerging field with strong

potential for adaptive integration [11], notably in dynamic contexts involving continuous learning [12].

Meanwhile, “decision making” serves as a bridge between technical and cognitive approaches, relating to “real-time systems”, “human-machine interface”, and “human-computer interaction”. It demonstrates that supervision goes beyond data visualization; it also requires interpretation and action [13]. In the context of Brazilian biotechnology, the connection suggests the development of interfaces compatible with edge devices that support autonomy even in environments with limited data or infrastructure.

Taken together, these four terms reflect a trend in the literature: the strengthening of intelligent supervisory models, centered on the operator interface and supported by “process control”. The data also highlight innovation in biotechnology and bioprocesses, with a focus on Brazil, through

the development of adaptive and predictive “human-machine interfaces” capable of operating in uncertain environments, integrating biological data, and supporting real-time strategic decision-making.

Analysis using Bibliometrix

Topic Relevance Map

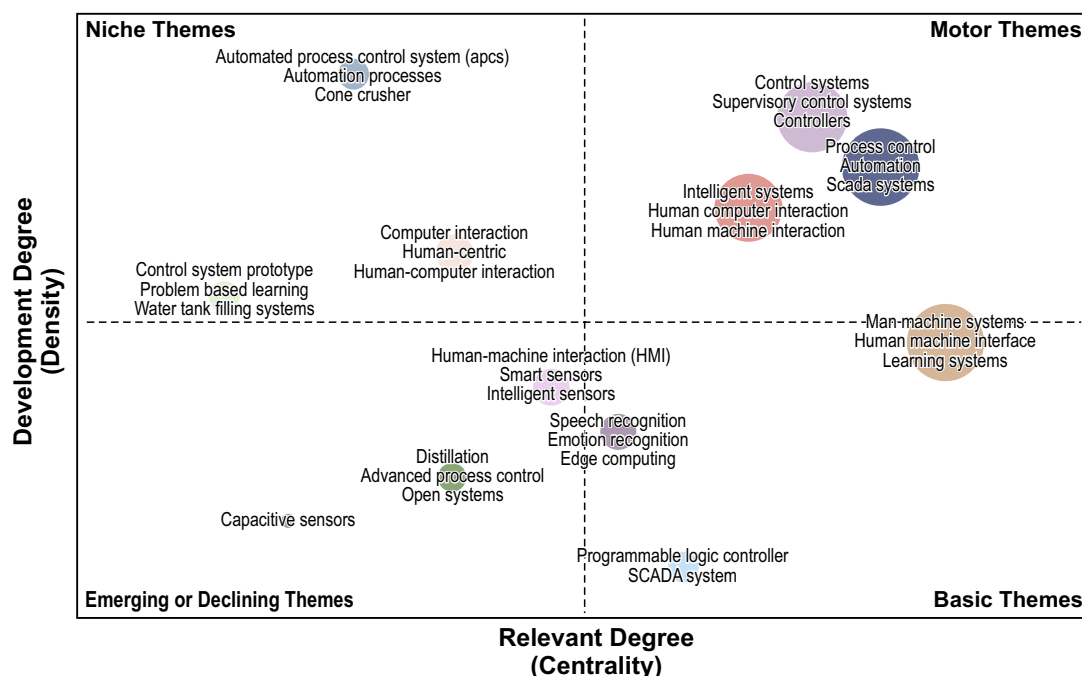
The thematic map generated by Bibliometrix distributes topics across four quadrants: "Motor Themes", "Basic Themes", "Niche Themes", and "Emerging or Declining Themes" (Figure 2). In this case, terms such as “process control”, “supervisory control systems”, “automation”, and “SCADA systems” appear in the upper right quadrant, indicating high density and centrality, which are well-developed and fundamental topics in the field. The position of these terms reinforces the historical dominance of technical control in supervisory systems. This is due to the essential role of supervision in the use of interfaces for task control, enabling rapid decision-making and high-

level language instruction, supported by tools such as simulations, which, while not inherent to automation, are critical at scale [14]. Demonstrate the importance of supervisory systems in process control.

The group of terms such as “human machine systems”, “human machine interface”, and “learning systems” are in transition between the Basic and Motor quadrants, suggesting that although initially structural concepts, they become central as adaptive processes. This growth is linked to systems that learn from human-machine interaction data, using self-adaptive mechanisms inspired by collective behavior. Techniques such as swarm intelligence are beginning to be applied to optimize decision-making and personalize care through adaptive content scheduling and real-time data display adjustments [15]. It is used to facilitate interaction with the interfaces, even if the user is not used to complex systems.

Terms such as “emotion recognition”, “smart sensors”, and “edge computing” appear with a low density, located in the lower quadrant. It may indicate that these areas, while still incipient,

Figure 2. A relevance map that organizes keywords into four sectors to show their importance and use in articles.



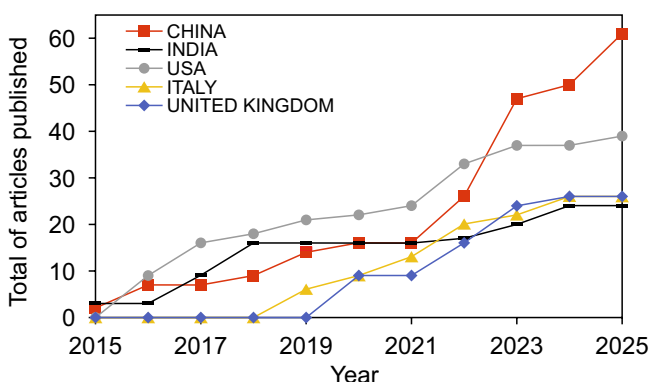
are emerging as relevant issues, particularly in the context of more sensitive and responsive interfaces. Their position invites reflection on the rise of approaches centered on human perception and behavior, particularly in light of predictions that computing will become invisible, integrated into all spaces, and put the user at the forefront, to make the experience more intuitive, contextual, and personalized [16]. This underscores the importance of autonomous systems and easy-to-use control-operated supervisory interfaces for new industries, where innovation and efficiency are essential.

Finally, the isolated position of “programmable logic controller” and “SCADA system” in the lower-right quadrant suggests that, despite their historical importance in once serving as the central control unit in industrial processes [17], these topics have not recently experienced the same pace of innovation as other topics, indicating a stabilization or potential need for conceptual updating.

Scientific Production Over Time

A temporal examination of scientific production from 2015 to 2025, based on Scopus data, revealed significant trends (Figure 3). The country evolution chart shows that China, the United States, and India were the main producers, with a sharp increase after 2021. This growth may be a

Figure 3. Country production over time in a graph with countries separated by color.



strategic response to the need for new autonomous control and supervision methods, especially after the COVID-19 pandemic, which highlighted the importance of automation for industrial resilience [1]. The rise of these countries, especially those with a strong industrial tradition, suggests a strategic response to the need for new autonomous control and supervision methods to replace human systems that were compromised by the limitations of physical distance [18].

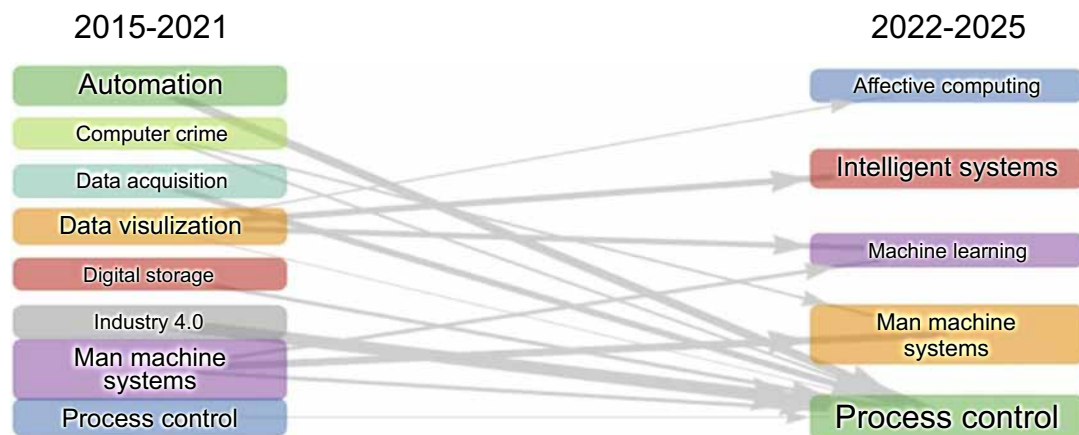
In addition, the absence of Brazil among the main producing countries, at least in the articles filtered in the research, raises questions about the level of national investment in applied research on the topic, possibly due to the computational cost demands [5], or even due to a possible dispersion of scientific production in areas not directly indexed or focused on other scientific perspectives. Such results show a gap area to be explored, even with little investment in the field, especially for biotechnological industries.

In addition to this perspective, there is also the evolution of keywords between the periods from “2015 to 2021” and from “2022 to 2025” as shown in Figure 4.

These reflect the major shifts in thematic focus. Terms such as “automation”, “data acquisition”, “Industry 4.0”, and “data visualization” have recently given way to topics such as “machine learning”, “affective computing”, and “intelligent systems”. This transition is related to a shift from structural technologies to those with greater cognitive and adaptive capacity [14], in line with the growing need for more humanized and context-aware systems. The prominence of “affective computing”, for example, suggests, as said before, an emerging interest in reading the emotional states of the operator, which is fundamental for decision-making based not only on technical variables, but also on behavioral ones [15].

By enabling precise control and process optimization, these interfaces reduce energy and resource use, minimize production and supply chain waste, improve safety, and lower environmental risks, thus aligning with key United Nations

Figure 4. Thematic evolution shows the evolution of the article's focus over time.



Sustainable Development Goals (SDGs) such as SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [19]. Although focused on bibliometric assessment, this study offers insights into integrating supervisory HMIs with HPC, intelligent sensing, and sustainable mobility solutions in the field.

Conclusion

The bibliometric research conducted using VOSviewer and Bibliometrix between 2015 and 2025 confirms a consistent growth in research on human-machine interfaces in autonomous and intelligent systems, with a stronger focus in industrialized countries. Examination of 99 publications enabled us to identify six main clusters, centred on terms such as 'human-machine interface', 'process control', 'machine learning', and 'decisionmaking'. Co-occurrence, geographical, and temporal distributions revealed an increasing trend towards the integration of artificial intelligence, supervision, and decision-making, as well as a notable surge in studies following the onset of the pandemic. However, significant gaps remain, such as low application in biosystems and the absence of Brazilian contributions, highlighting the need for greater national investment. Technological

evolution points to a transition from structural to cognitive and adaptive approaches. This reinforces the importance of multidisciplinary research to meet the demands of Industry 4.0, particularly in emerging economies.

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