Trends and Developments in Self-Adaptive Systems: A Bibliometric Analysis on IoT and Green Computing Integration

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Abstract

The integration of the Internet of Things (IoT) into Self-Adaptive Systems (SAS) is highly significant for areas such as Green Computing, especially given the pressing challenges of pollution and global warming. These systems are being incorporated into a wide range of appliances as well as urban and industrial infrastructure, fundamentally changing both our daily lives and the technological landscape. This paper investigates the current state of self-adaptive systems in IoT and Green Computing applications through an extensive bibliometric analysis. Utilizing data from several reputable academic sources, including IEEE Xplore, this study employs thorough statistical analysis and visualization of systematically collected data. The findings reveal a strong correlation between research groups and the frequent co-occurrence of indexing terms associated with IoT and Green Computing. The results are presented in various formats, including tables, graphs, and network diagrams, to ensure clarity and facilitate understanding. This study aims to offer more than just superficial insights into the SAS field, providing guidance for future research and development initiatives in the integration of self-adaptive systems with IoT and Green Computing technologies.

Keywords

Self-Adaptive Systems, Internet-of-Things, Green Computing, Energy Consumption, Bibliometric Analysis

1. Introduction

The growing integration of self-adaptive systems within IoT-based platforms is fostering innovation in green computing. This convergence harnesses the adaptability and intelligence of IoT devices while adhering to the energy-efficient principles of green computing. Consequently, merging self-adaptive IoT systems with green computing principles presents significant benefits and challenges. The primary advantages include improved energy efficiency through optimized resource utilization and a reduced environmental impact [1]. Furthermore, incorporating green computing can enhance decision-making by providing real-time information regarding energy consumption and environmental parameters [2]. However, both self-adaptive systems and IoT exhibit distinct characteristics that pose complex design and practical challenges [3, 4], which may impede the full realization of their combined benefits [5]. These challenges encompass interoperability, scalability, heterogeneity, complexity, and security, all of which system designers must tackle to effectively manage the continual evolution of diverse systems and identify unforeseen behaviors resulting from their interactions [6, 7].

To address these intricate characteristics, various strategies have been explored, including hybrid design approaches [10], practical solutions [9], and an array of tools and frameworks [8, 11]. These initiatives aim to bridge the divide between theory and practice, with applications across different stages of the engineering process such as conceptual modeling [12], practical design [13], simulation [14], and

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post-deployment quality assessment and validation [15]. In this paper, we utilize a systematic approach to investigate recent advancements in self-adaptive systems in the context of IoT and green computing. Our methodology includes a bibliometric analysis, which quantitatively assesses scholarly excellence through indicators such as publication activity, significant articles and journals, co-authorship patterns among countries, keyword co-occurrences, and other relevant metrics within the research domain [16, 17, 18, 19, 20]. This approach is essential for collecting and interpreting comprehensive data while minimizing subjective biases in the study of self-adaptive IoT systems and their integration with green computing. By employing advanced bibliometric techniques and visualization tools, researchers can identify key contributors, collaborative networks, research themes, and influential works within the evolving landscape of IoT research [21, 22]. The organization of this paper is as follows: Section 2 outlines the methodology employed in this study. Section 3 presents the findings from our bibliometric analysis. Section 4 discusses the implications of these findings. Section 5 addresses the limitations encountered throughout the study. Lastly, Section 6 concludes the paper by summarizing the results and suggesting potential directions for future research.

2. Methodology

In this section, we outline the structured methodology utilized to perform a comprehensive bibliometric analysis, which encompass the collection, processing, and analysis of data, as depicted in Figure 1:

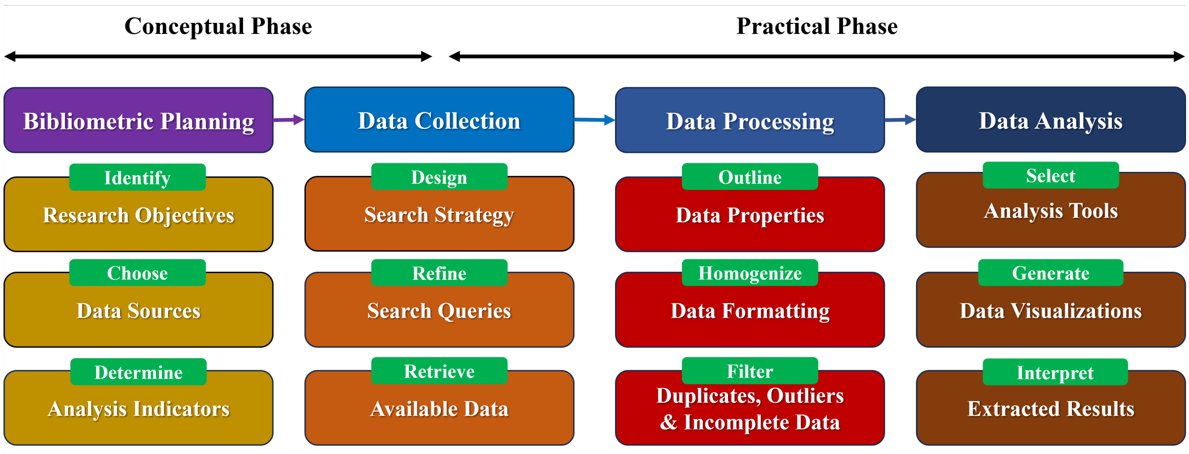

Figure 1: Summary of the Bibliometric Analysis Process

1. **Bibliometric Planning:** The initial phase of our approach is bibliometric planning, where we establish our research objectives by formulating specific research questions, selecting suitable data sources, and identifying key indicators. This stage serves as the cornerstone of our study.
2. **Data Collection:** During this phase, we systematically gather pertinent scholarly articles from established databases using targeted keywords and advanced search strategies.
3. **Data Processing:** Following data collection, we focus on processing the gathered articles. This involves cleaning the dataset by eliminating duplicates and irrelevant entries, standardizing author names and affiliations, and ensuring that all data entries are complete. We also format the data to prepare it for analysis, extracting essential metadata such as publication year, citation counts, and journal details.
4. **Data Analysis:** In this final step, we select appropriate tools and methodologies for statistical analysis and visualization. We create charts and graphs to interpret the data and derive insights that address our research questions regarding the integration of self-adaptive systems, IoT, and green computing.

2.1. Bibliometric Planning

The first stage of our methodology involves bibliometric planning, which encompasses several essential tasks. We begin by defining our research objectives, clearly outlining the aims of our study. We strive to approach this step objectively, drawing inspiration from the Goal-Question-Metric model [23]. Our research focuses on two primary aspects, for which we will establish corresponding goals.

2.1.1. Goal 1

Evaluate the novelty of research in Self-Adaptive Systems, particularly concerning its integration with "Green Computing" and "Internet-of-Things."

Question 1: What are the highly trending fields of research associated with self-adaptive systems in recent years?

Question 2: Are "Green Computing" and "Internet-of-Things" among the fields of study adjacent to "Self-Adaptive Systems"?

Question 3: Does the data favor the idea of "Green Computing" and "Internet-of-Things" being somewhat novel domains for Self-Adaptive applications?

2.1.2. Goal 2

Provide a general overview of the most significant and influential individuals or groups contributing to the advancement of the selected topics, namely Self-Adaptation, Green Computing, and the Internet-of-Things.

Question 4: What/Who are the most active/mentioned contributors in the field of Self Adaption, Green Computing and Internet-of-Things recently?

Question 5: What/Who are the most cited contributors in the field of Self-Adaptive Systems, Green Computing and Internet-of-Things recently?

In addressing these questions, bibliometric indicators will function as metrics, as suggested by the GQM method, to evaluate the foundation of the analysis and provide meaningful feedback on the results discussed further in Section 4. For our investigation into self-adaptive systems, IoT, and green computing, we concentrated on specialized databases recognized for their extensive coverage in computer science literature. The primary sources chosen were ACM Digital Library, IEEE Xplore, and DBLP (Digital Bibliography Library Project).

These platforms are esteemed for their vast collections of peer-reviewed articles, conference proceedings, and technical reports pertinent to our research topics. We selected ACM and IEEE Xplore because of their focus on computer science and engineering disciplines, ensuring that our data collection concentrated on high-quality, authoritative sources within our field. DBLP further enhanced these databases by offering a comprehensive index of computer science publications, including conferences and journals.

While Google Scholar was considered for its broad coverage across various disciplines, it was ultimately excluded from our data collection strategy due to its tendency to retrieve multidisciplinary results, which often include lower-quality and less relevant articles for our specific research focus. Additionally, we investigated Semantic Scholar for its advanced research capabilities and pertinent content in computer science. Despite its coverage of multiple disciplines, its focus on academic research and robust search functionalities provided a promising avenue for obtaining high-quality and relevant publications.

To extract data from Semantic Scholar, we employed their API to access detailed research results in a structured JSON format. Ultimately, we identified several key analysis indicators that will serve as metrics to thoroughly analyze our dataset and respond to the research questions posed at the outset. These metrics encompass publication counts per year, citation counts for leading publications, author contributions, co-authorship patterns, keyword co-occurrence, and institutional affiliations based on citation and contribution counts across countries and institutions.

2.2. Data Collection

We commenced the data collection process by performing searches on July 5th, 2024, across several high-impact research databases. For each database, we executed two sophisticated queries to ensure comprehensive coverage, with the retrieved data summarized in Table 1. The specific queries utilized are presented below:

Query 01: ("self-adaptive systems" OR "SAS" OR "auto-adaptive systems") AND ("IoT" OR "Internet of Things")

Query 02: ("self-adaptive systems" OR "SAS" OR "auto-adaptive systems") AND ("green computing" OR "energy-efficient computing")

Table 1
Details Gathered Data For Each Data Source

Source	Query	Quantity	Format	Metadata Fields										
				Pub. Title	DOI	Authors	Affiliations	Countries	Doc. Type	Pub. Year	Citations	Ref. Count	Keywords	Abstract
IEEE	01	52 Paper	.csv	x	x	x	x		x	x	x	x	x	x
IEEE	02	13 Paper	.csv	x	x	x	x		x	x	x	x	x	x
Semantic	01	706 Paper	.json (API)	x	x	x			x	x	x	x		x
Semantic	02	1000 Paper	.json (API)	x	x	x			x	x	x	x		x
ACM	01	37 Paper	.bib	x	x	x		x		x			x	x
ACM	02	157 Paper	.bib	x	x	x		x		x			x	x
DBLP	01	73 Paper	.json	x	x	x			x	x				
DBLP	02	29 Paper	.json	x	x	x			x	x				

The searches conducted in each database were carefully refined using advanced command searches and specific keywords that aligned with the objectives of our study. Filters were applied to target only journal publications from 2014 to 2024, ensuring both relevance and novelty. Due to the large volume of results, the data were organized according to citation counts and relevance. The resulting documents were then exported in CSV format, containing essential metadata about 2,067 papers, including titles, authors, affiliations, publication years, DOIs, citation counts, and keywords.

2.3. Data Processing

In processing our data, we initially converted all files from CSV or BibTeX formats to JSON using a Python script. For each dataset, we ensured consistency by preserving essential attributes such as title, DOI, author list, institute list, publication year, keywords, citation count, and source (e.g., IEEE, ACM). We standardized the format of these properties across all datasets. To further enhance uniformity, we incorporated additional data consistently. For instance, within the ACM dataset, we created a Python script to query and append institute information to each object using the CrossRef API. Additionally, we utilized another Python script to ensure that the order of authors corresponded to their respective institutes for consistency.

To maintain coherence in author names across various sources, we employed the CrossRef API to query and standardize author names. Likewise, for the location (country), we retrieved and standardized country names from CrossRef detailed locations, eliminating multiple abbreviations for the same country through supplementary Python scripting. A few entries were systematically merged in the initial pool of 2,067 papers, reducing the total to 1,957. After consolidating all datasets, we conducted post-processing on the data to identify and eliminate duplicate entries, merging their content into a single record. This refinement resulted in the data decreasing from 1,957 to just 1,608 papers, indicating that 349 pairs of duplicates were matched based on DOIs across different data sources.

2.4. Data Analysis

In the data analysis phase, we utilized the Python programming language alongside the Pyplot library to create visualizations. We opted for Python due to its versatility in managing large datasets and its comprehensive libraries for data manipulation and analysis. Pyplot was specifically selected for its powerful features in generating a wide range of charts and graphs, which are crucial for visualizing bibliometric data. Based on this, we produced several visualizations, including:

- **Publication Analysis:** We utilized a line chart to visualize the annual growth in publications and a table to highlight the most cited publications.
- **Author Analysis:** Bar charts were employed to illustrate the most cited and contributing authors, supplemented by a heatmap to depict co-authorships.
- **Keyword Analysis:** Heatmaps were used to show keyword co-occurrences, with line charts tracking trends for relevant keywords over time.
- **Affiliation Analysis:** For analyzing affiliations, pie charts illustrated country distributions based on citation and contributions, while detailed tables presented information on the most cited institutions.

3. Findings

After executing all queries and processing the data, we assembled a comprehensive dataset that serves as the basis for our study. The bars in Figure 2 depict the distribution of publications across the different selected data sources, showcasing our efforts in gathering and curating relevant literature from specialized sources.

Figure 2: Publications Distributed per Data Source

3.1. Publication Analysis

- **Publications In Recent Years:** In our analysis, we divided our dataset to differentiate publications centered on self-adaptive systems (SAS) and the Internet of Things (IoT) from those focused on SAS and green computing. Figure 3 displays trends in publications over the last decade, featuring two lines: one representing SAS and IoT, and the other representing SAS and green computing. This combined chart enables to compare and contrast the evolution of these two thematic areas within the wider domain of self-adaptive systems.

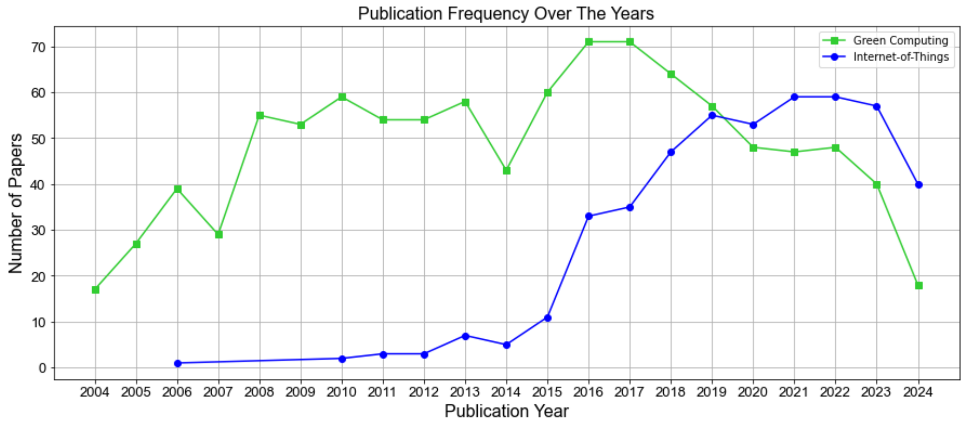

Figure 3: Quantity of Publications per Year

- **Most Cited Publications:**
  Table 2 highlights the top 10 most cited papers within our dataset, offering a detailed view of the publications that have made the most substantial impact in the fields of self-adaptive systems, IoT, and green computing. This analysis not only underscores the influence of these foundational works but also provides a window into the major research trends that have shaped the evolution of these domains. By reviewing these highly cited publications, we can discern critical themes and methodologies that have driven innovation, influenced subsequent research, and contributed to solving complex challenges associated with interoperability, energy efficiency, and system adaptability. This analysis allows researchers and practitioners to identify key contributors and methodologies that are central to this area, helping to inform their own work and foster further advancements. Additionally, understanding the key ideas from these impactful papers can provide insight into potential areas for collaboration and highlight gaps in the literature that future research might address, thus helping to drive the field forward.

Table 2
Most Cited Publications

Rank	Authors	Reference	Citations
1	DeTone, D., Malisiewicz, T., Rabinovich, A.	[24]	1796
2	Qin, Z., Denker, G., Giannelli, C., Bellavista, P., Venkatasubramanian, N.	[25]	357
3	Prikler, L. M., Wotawa, F.	[26]	311
4	Sharifloo, A. M.	[27]	311
5	Muccini, H., Sharaf, M., Weyns, D.	[28]	230
6	Ataguba, J. E.	[29]	213
7	Griebel, L., Prokosch, H. U., Köpcke, F., et al.	[30]	211
8	Gil De La Iglesia, D., Weyns, D.	[31]	202
9	Balsamo, D., et al.	[32]	190
10	He, X., Wang, K., Huang, H., Miyazaki, T., Wang, Y., Guo, S.	[33]	190

3.2. Authorship Analysis

- **Most Cited and Contributing Authors:**
  The bar charts in Figure 4 illustrate the top 20 most cited and contributing authors from our dataset, showcasing those who have made substantial impacts in the field of self-adaptive systems, IoT, and green computing. These charts not only highlight the leading contributors but also provide a clear visualization of their influence based on citation counts and research output. By

identifying these key authors, we gain insights into the individuals driving the research forward and shaping the ongoing developments in this evolving domain. This analysis serves as a valuable reference for recognizing major research trends.

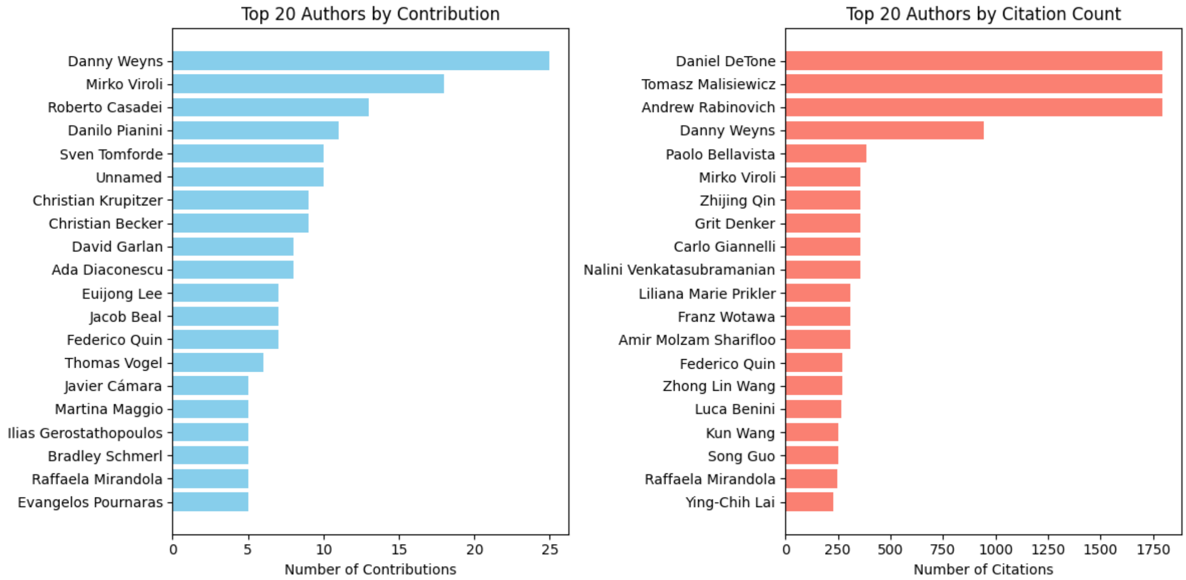

Figure 4: Most Active Authors and Most Influential Authors Side-by-Side

- **Co-authorship:**
  Figures 5 and 6 present an in-depth analysis of co-authorship, specifically highlighting the top 20 authors based on both citations and contributions within the dataset. This analysis not only uncovers the collaborative networks among prominent researchers but also sheds light on the key contributors driving innovation in self-adaptive systems, IoT, and green computing.

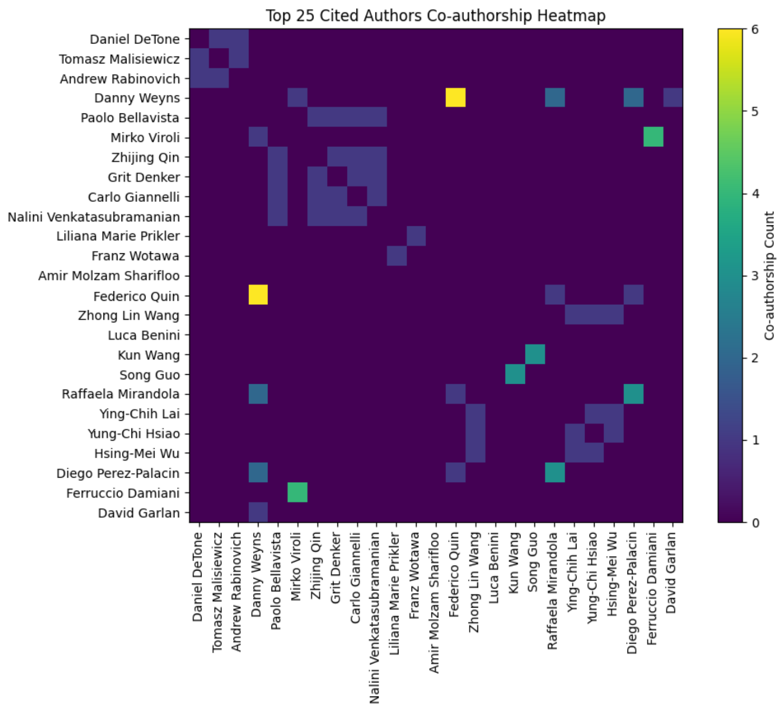

Figure 5: Co-Authorship Heatmap for Most Cited Authors

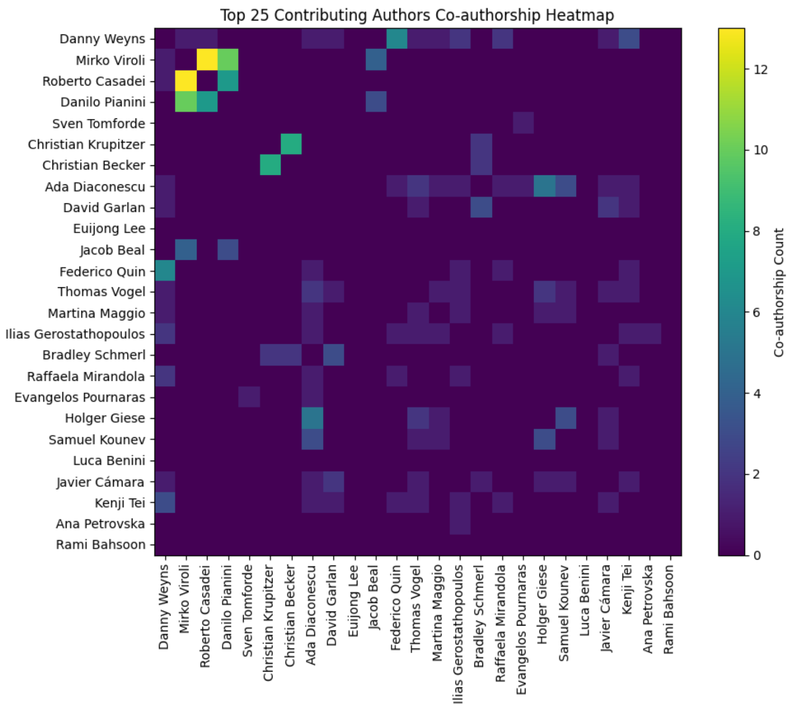

Figure 6: Co-Authorship Heatmap for Most Active Authors

3.3. Keyword Analysis

- **Keywords per Year:** Figure 7 presents our analysis of keyword trends over time, based on 442 keywords identified throughout the dataset. This visualization highlights how specific terms have gained prominence over the years, offering insights into the shifting research focuses within the fields of self-adaptive systems, IoT, and green computing.

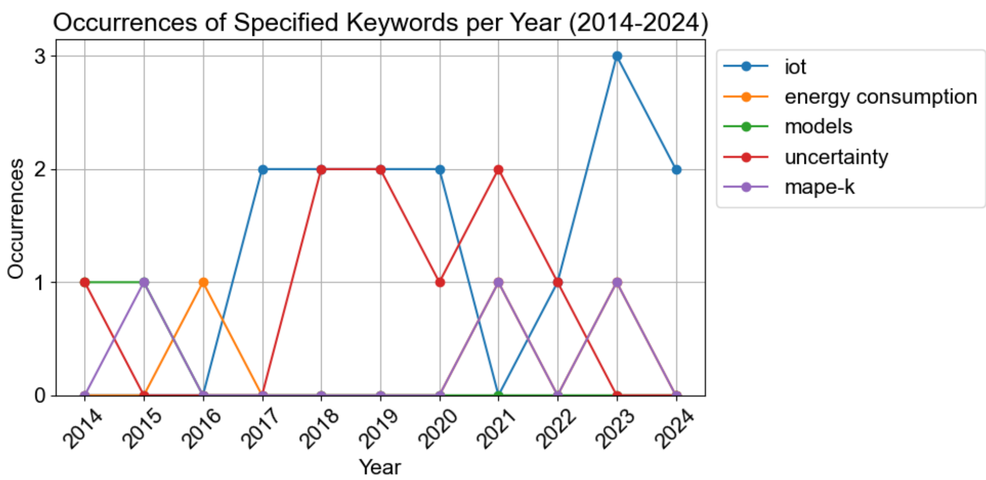

Figure 7: Occurrence of Top 5 Relevant Keywords Over the Years (2014-2024)

- **Keywords Co-occurrence:** The heatmap in Figure 8 illustrates the co-occurrence of keywords, focusing on the top 25 most cited terms within our dataset. This visualization explores relationships among these influential terms, revealing themes and areas of convergence to the main topic of study.

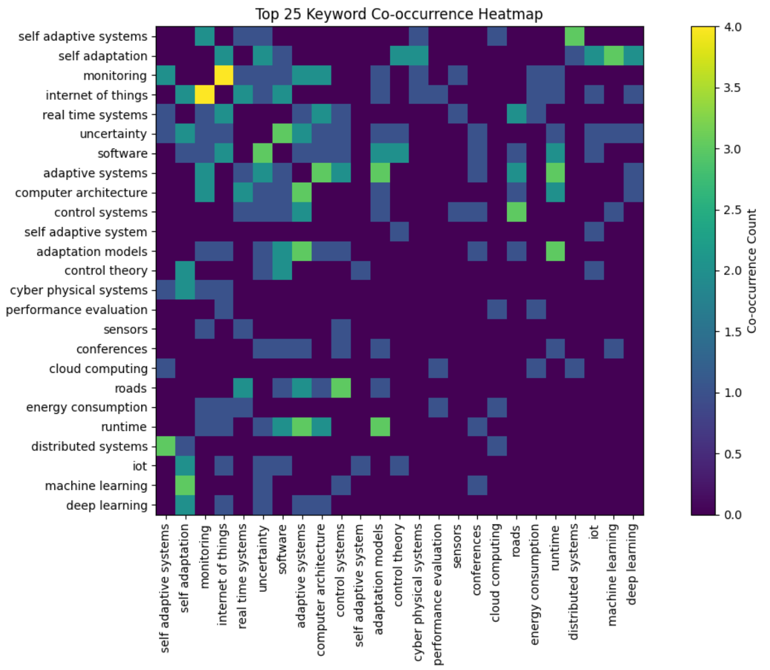

Figure 8: Keyword Co-Occurrence Heatmap for Most Mentioned Keywords

3.4. Affiliation Analysis

- **Contributions per Country:** In this analysis, we cover a total of 187 countries. Leading in contributions are the USA with 234, followed by the UK and Germany. These findings are presented through a pie chart in Figure 9, showcasing the distribution of contributions across the top 15 countries.

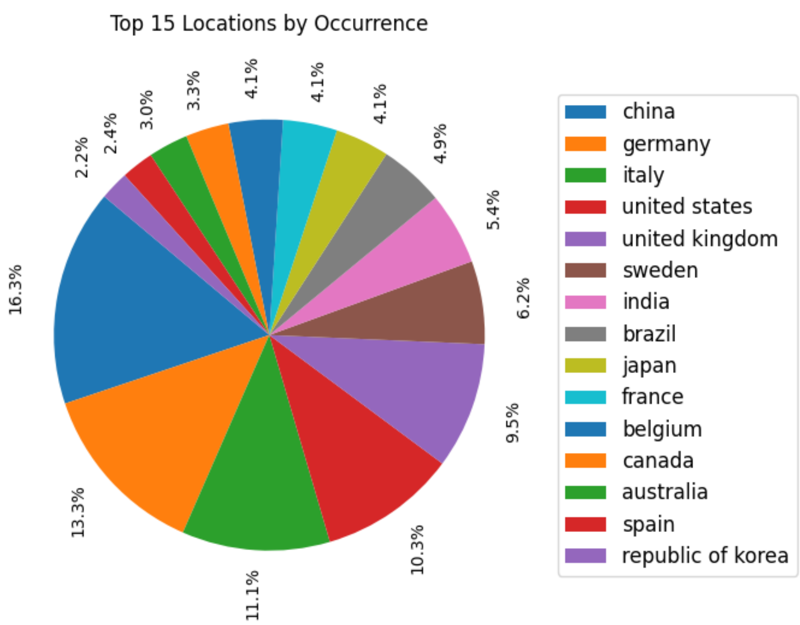

Figure 9: Most Active Countries Pie Chart

- **Citations by Country:** Our analysis of citations by country within the field of self-adaptive systems and related areas reveals nations with the highest citation counts: lead by USA highest count of citations, followed by the United Kingdom and Germany. Using a pie chart in Figure 10, we visually depict the distribution of citations among the top 15 countries.

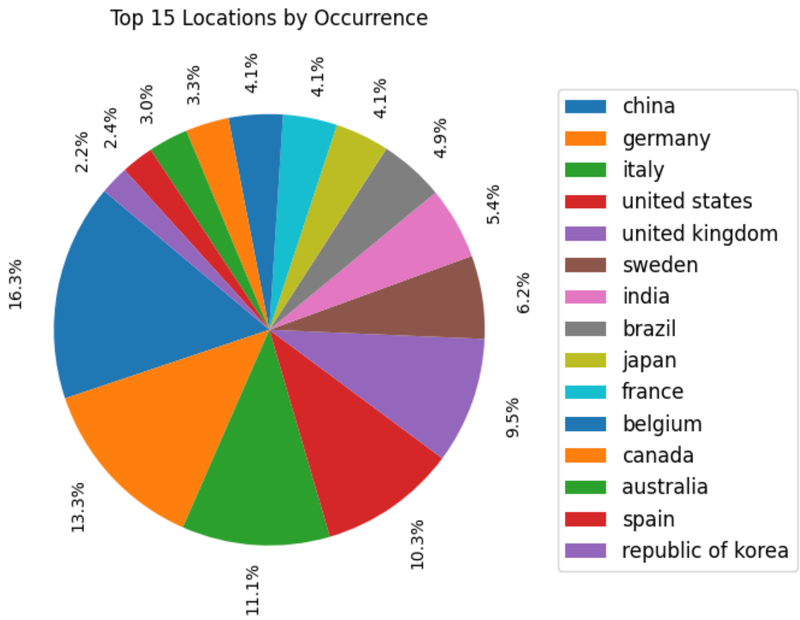

Figure 10: Most Cited Countries Pie Chart

- **Analysis of Influential Institutes, Citations, and Contributions:** This section explores an analysis of prominent institutes based on their citation impact and research contributions in the field of self-adaptive systems and related disciplines. We highlight institutions that have achieved notable citations and contributed significantly to advancing research. Table 3 presents the top seven institutes based on contribution count, while Table 4 highlights the institutes that have made the most recently significant contributions to research in this field in terms of citation count.

Table 3
Top Institutions by Contribution Count

Rank	Institution	Contributions
1	Department of Electrical and Computer Engineering, National University of Singapore, Singapore	12
2	The Ohio State University, USA	11
3	Politecnico di Milano, Italy	10
4	Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano and IU.NET, Italy	10
5	KU Leuven Department of Materials Engineering, Belgium	10
6	Carnegie Mellon University, USA	9
7	Dresden University of Technology, Germany	9

Table 4
Top Institutions by Citation Count

Rank	Institution	Citations
1	Department of Electrical and Computer Engineering, National University of Singapore, Singapore	1968
2	Department of Materials Science and Engineering, National Chung Hsing University, Taiwan	690
3	Graz University of Technology, Austria	622
4	Linnaeus University, Sweden	471
5	Katholieke Universiteit Leuven, Belgium	429
6	University of California, Irvine, USA	350
7	Politecnico di Milano, Italy	340

4. Discussion

Following the GQM framework, metrics were defined to evaluate each question related to bibliometric indicators. The first goal (G1) was achieved by addressing Q1, Q2, and Q3:

1. For Q1, Figure 8 shows that Self-Adaptive Systems (SAS) frequently co-occur with keywords like "Distributed Systems" and "Machine Learning," highlighting their relevance in recent research and it demonstrates a strong association between SAS and these fields.
2. In Q2, Figures 7 and 8 indicate a recurring integration of IoT with SAS, while "Green Computing" is less prominent, suggesting limited exploration. These figures confirm that IoT is increasingly featured in SAS research, whereas Green Computing remains underrepresented.
3. Regarding Q3, Figure 7 shows the rise of IoT-related terms in SAS over time, while Figure 3 illustrates a decline in Green Computing publications, reinforcing the idea that IoT's integration with SAS is gaining momentum, but Green Computing needs more attention.

The novelty of SAS research is evident, particularly in its integration with IoT. However, further exploration of Green Computing in this context is necessary. The second goal (G2) was addressed by:

4. For Q4, Figures 4, 5, and Table 3 reveal the most active and influential authors, key collaborative efforts, and leading institutions in SAS, IoT, and Green Computing.
5. Q5 is evaluated through Figures 4, 10, and Table 4, which show the most cited contributors and institutions, highlighting the global and institutional leaders driving these fields.

5. Limitations

Our study faced several limitations that impacted the comprehensiveness and efficiency of our analysis. One of the primary challenges was the scarcity of information regarding green computing, as shown in Table 1, due to inaccessibility and technical barriers with certain research databases (Springer, Elsevier, Scopus), we were constrained in accessing a broader range of sources. This limitation potentially excluded relevant publications that could have contributed to a more comprehensive analysis. This limitation restricted the depth of our analysis in this specific area. Additionally, the gathered data had several gaps, particularly in keywords from Semantic Scholar and DBLP, as well as authors' affiliations, which were only consistently available in IEEE. This inconsistency required us to repeatedly collect data using the CrossRef API to complement the missing information. However, this approach was not as effective as expected, as not all the necessary data was found in the API. Furthermore, the formatting process for multiple data properties was time-consuming due to the differences in data structures and properties across sources. This added an extra layer of complexity to the data processing workflow and extended the overall time required for preparing data.

6. Conclusion

This study is meant to highlight the evolving nature of research in Self-Adaptive Systems, particularly their integration with IoT and their use for green purposes. Key contributors and trending themes were determined providing insight into the recent status and potential directions of SAS, although, our efforts were initially aimed to identify research gaps in fields adjacent to SAS. Despite the considerable volume of resulting data, no easy conclusions could be drawn.

Looking ahead, the intersection of SAS and Green Computing presents promising opportunities for innovation. Our future work will be centered on exploring this hybrid field, as we aim to propose intelligent approaches for optimizing energy consumption and contributing to the development of efficient, robust, and environmentally sustainable systems.

7. Declaration on Generative AI

During the preparation of this work, the authors utilized ChatGPT to assist for grammar and style enhancements throughout the manuscript, particularly in drafting and refining the "Abstract", "Introduction", and "Conclusion" sections. Following the use of this tool, the authors thoroughly reviewed and edited the content to ensure clarity, coherence, and alignment with the research objectives. The authors take full responsibility for the final version of this publication.

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