Preliminary Bibliometric Analysis of Artificial Intelligence Methods Applied to In-Core Fuel Management and Radioactive Waste Management

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ABSTRACT

For almost seventy years nuclear energy has been used for electricity production. With more than 400 currently operable reactors, and more than 200 reactors being shutdown, there are a lot of accumulated operational data. In addition, worldwide application of computer simulations in nuclear reactors design generates large quantities of data. This creates the fundamental step for artificial intelligence technology, which experiences exponential growth over the last couple of decades, to be applied in the nuclear technology field.

Literature review is an important part of scientific research examining the general state of a research field, categorizing existing knowledge, and identifying potential gaps to be filled. Growth in the production of scientific knowledge with rapid increase in the number of academic journals, conferences, and other scientific publications, raises the need for rigorous technique to be used for exploring and analysing the literature which goes beyond the classical literature review.

Therefore, the aim of this paper is to employ rigorous bibliometric analysis of artificial intelligence methods, primarily machine learning, deep learning, and evolutionary computing, applied to in-core fuel management and radioactive waste management. The overall goal is to identify core ideas shaping the particular area, currently persisting challenges, and research evolution.

Keywords: *keyword1, keyword2, keyword3, keyword4, keyword5*

1 INTRODUCTION

In order to achieve sustainable economic development, i.e., to fulfil needs of present and future human generations while preserving natural environment, low-carbon policies are being advocated and implemented by governments all over the world. The key goal of such policies is to reduce the consumption of high-carbon sources and greenhouses gasses emissions as much as possible [1]. Nuclear energy is a carbon-free, reliable source of energy, and as such presents a viable alternative to high-carbon fossil fuels [2]. However, to profile nuclear energy as competitive and integrable in modern sustainable power energy systems, further effort is needed to enhance nuclear power plants' economic indicators, safety, and reliability [1].

In the last couple of decades integration of information technology with science and industry is gaining popularity. Various artificial technologies (AI) have been used in many scientific fields to speed up discoveries and knowledge accumulation [3], while in industry AI technologies help reduce the costs, improve profit margins, and enhance industrial competitiveness [4]. Modern AI technology is heavily dependent on data. Nuclear energy has been used for electricity production for almost seventy years, with more than 400 currently operable reactors, and more than 200 reactors being shutdown. During that period vast amount of operational data has been accumulated.

In addition, worldwide application of computer simulations in all aspects of nuclear energy power application generates large quantities of data. This creates the fundamental step for artificial intelligence technology to be applied in the nuclear technology field. Two areas of the nuclear technology field have been selected for bibliometric analysis: in-core fuel management and radioactive waste management. In the former one different types of optimization procedures have been used for a long time, prior to AI emerging. In the latter one, optimization has been employed on a much lesser scope. Therefore, the contrast of these two areas represents an interesting subject for bibliometric analysis to be employed.

A brief introduction to modern AI methods is given in section 2, while in section 3 main characteristics of bibliometric analysis are presented. The results of the preliminary bibliometric analysis of AI methods applied to in-core fuel management and radioactive waste management are presented in section 4, followed by conclusion in section 5.

2 BRIEF INTRODUCTION TO MODERN AI METHODS

AI is the science and engineering domain concerned with the theory and practice of developing systems that exhibit the characteristics we associate with intelligence in human behavior like ability to reason, discover meaning, generalize, or learn from past experience [5]. To perform these tasks the systems use complex computational processes.

In general, there are five AI categories [6]:

- Analytical AI – extracting insights from data and thus producing recommendations for data-driven decision making,
- Functional AI – similar to analytical AI, but instead of recommendations, resulting in actions,
- Interactive AI – automate communication,
- Textual AI – textual analytics, and
- Visual AI – computer vision or augmented reality.

To build AI-based models different AI techniques are used, which can be classified into ten categories:

- machine learning
- neural networks and deep learning
- data mining, knowledge discovery and advanced analytics
- rule-based modeling and decision-making
- fuzzy logic-based approach
- knowledge representation, uncertainty reasoning, and expert system modeling
- case-based reasoning
- text mining and natural language processing
- visual analytics, computer vision and pattern recognition
- hybridization, searching, and optimization

For each of these techniques there are a number of methods employed. The focus of this research is on machine learning, deep learning, and evolutionary computing, generally based on genetic algorithms, as an optimization technique falling into the last of the previously mentioned categories. A wide variety of machine learning methods and deep learning methods are graphically depicted in Figure 1 [6] and Figure 2 [7], respectively.

Such a diversity of methods represents a challenge for bibliometric analysis, especially for the process of bibliometric data collecting. Another problematic issue is lack of uniform categorization of AI techniques and methods, which is highly dependable on authors and used sources.

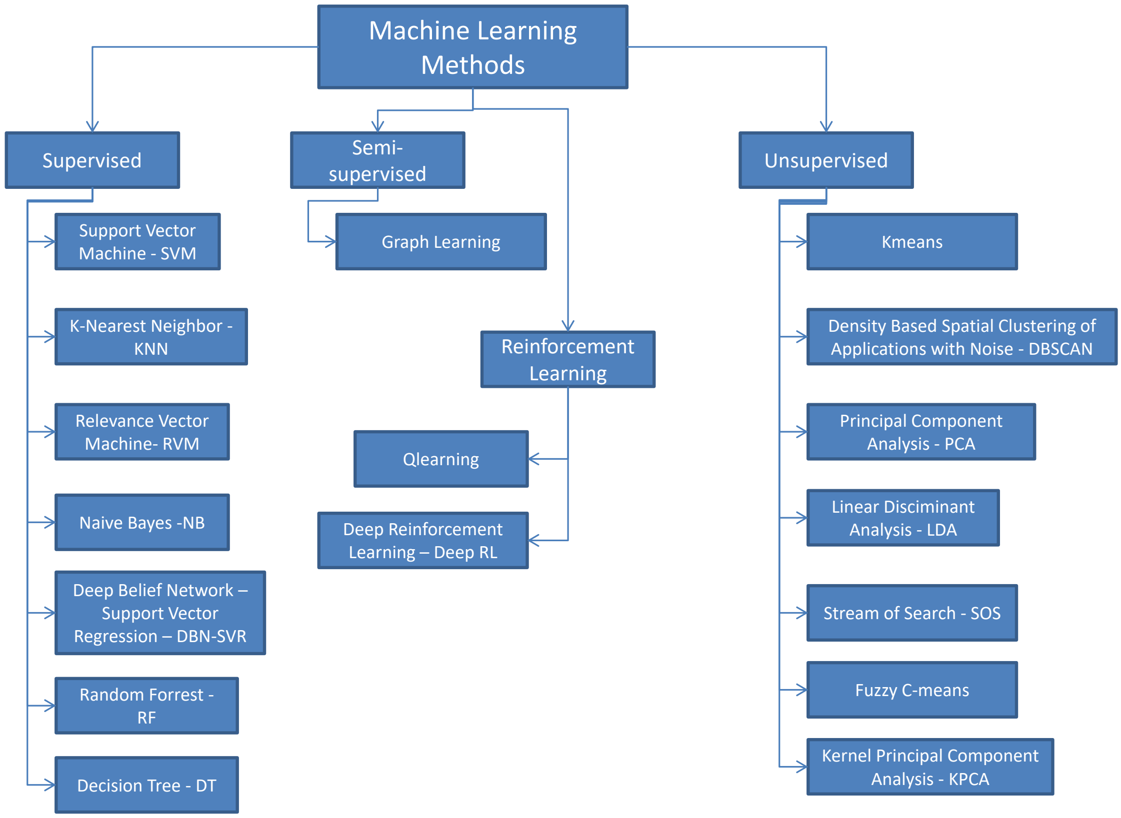

Figure 1: Machine learning methods

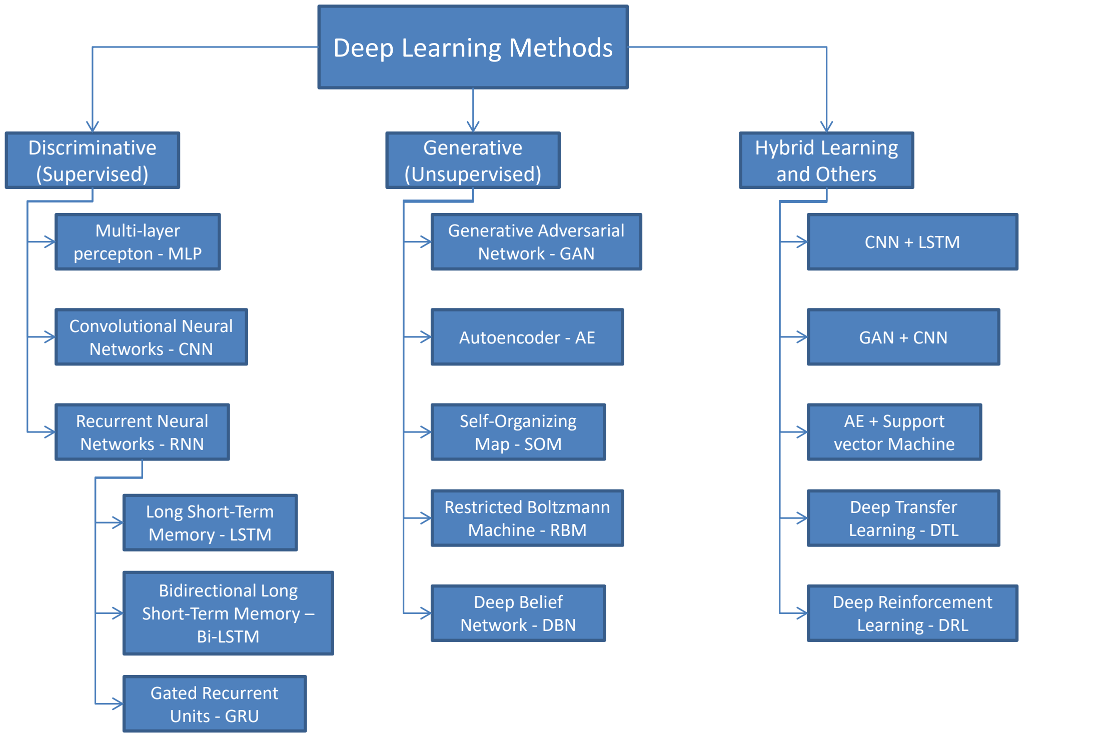

Figure 2: Main deep learning methods

3 MAIN CHARACTERISTICS OF BIBLIOMETRIC ANALYSIS

Literature review is an important first step in design a research, aiming to collect existing knowledge and examine the state in the field of interest [8]. There are several methods employed for that task, namely Classical Literature Review (CLR), Systematic Literature Review (SLR), Bibliometric Analysis (BA), and Meta Analysis (MA). The methods differ in their approaches and the types of data they analyse.

Both CLRs and SLRs can be author-centric or, more commonly, theme-centric in their orientation. In a theme-centric review, the researcher guides the reader through previous publications and their contributions to the theme of interest. For example, Huang et al. [9] performed a classical review on the application of artificial intelligence to nuclear reactors. The authors address 33 articles dealing with AI in nuclear reactor design optimization, and 38 articles employing AI in nuclear reactor operation and maintenance. However, the authors do not indicate the database used as a pool for articles selection, or the method used for selecting the articles, which are in general the main flaws of the CLR. Therefore, the replicability of the research is questionable and opens the question of author induced bias in the selection process. Adding missing elements to the review would result is SLR, which enables other researchers to reproduce the findings. Both, CLR and SLR are qualitative methods that summarize and synthesize the findings of existing literature.

BA and MA are quantitative methods capable of dealing with much larger datasets than SLR. MA summarizes the empirical evidence of relationship between variables found in existing literature while uncovering relationships not studied previously. BA summarizes large quantities of bibliometric data to present the state of the intellectual structure and emerging trends in the targeted field [10]. Comparison of the literature review methods is given in Table 1.

Table 1: Comparison of literature review methods

Review Method	**Goal**	**When to use**	**When not to use**	**Scope**	**Dataset**	**Analysis method**
SLR	Identify, evaluate, and synthesize existing research	Specific scope and dataset small enough for manual processing	Broad scope or too large dataset for manual processing	Specific	Small;	Qualitative (evaluation and interpretation)
MA	Combine results from multiple studies revealing new relationships between research variables	Homogenous studies in adequate quantity	Heterogeneous studies Low number of homogenous studies	Specific Broad	Small Large	Quantitative (evaluation and interpretation)
BA	Quantitatively analyse research output	Broad scope Dataset too large for manual processing	Specific scope Small dataset adequate for manual processing	Broad	Large	Quantitative (evaluation and interpretation) Qualitative (interpretation)

There are two main categories of BA techniques, namely performance analysis and science mapping [10].

Performance analysis investigates the contributions of research components (authors, institutions, countries, and journals) to the area of interest expressing the results in a number of different metrics, like total number of publications (TP), number of contributing authors (NCA), total number of citations (TC), collaboration index (CI), h-index (h), etc.

Science mapping (citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis) investigates the relationships between research components. For example, citation analysis discovers the most important articles in the field presuming that these are also the most cited articles by other publications. Co-word analysis focuses on words, extracted from keywords, titles, or abstracts assuming that words that appear together have a thematic relationship with one another.

To enrich BA analysis and enable easier understanding of the results, there are, so called, enrichment BA techniques like network metrics, clustering and visualization.

Different BA techniques are graphically depicted in Figure 3 [10].

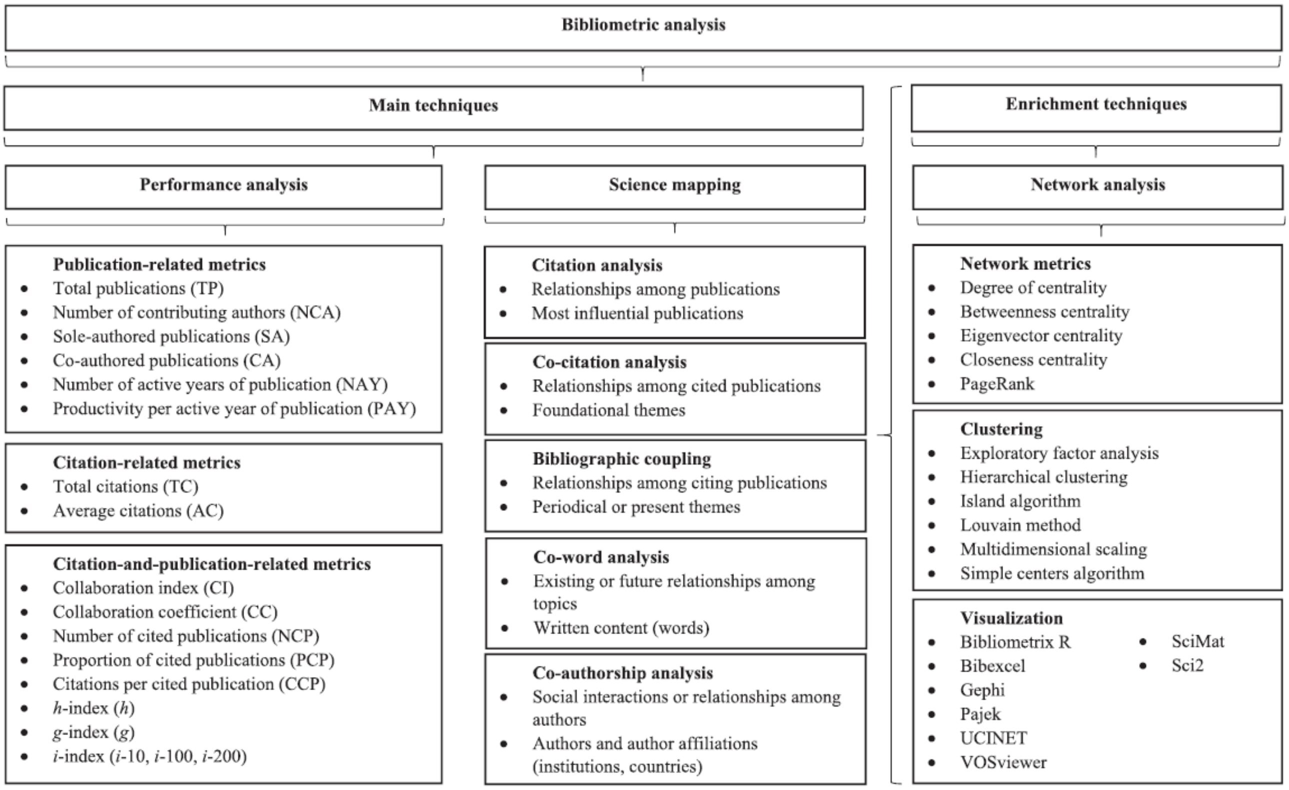

Figure 3: Bibliometric analysis techniques [10]

There are four main steps in performing BA:

1. Defining the aims and scope of bibliometric study following guidelines given in Table 1,
2. Choosing the appropriate BA techniques to be used in the study based on aims defined in previous step,
3. Collecting the data for BA, which includes designing the search term, selecting database, obtaining the search results and cleaning the data from duplicates
4. Running BA and reporting the results

In the proceeding section, each of these steps will be correlated to this research's area of interest, AI implementation in the field of in-core fuel management and radioactive waste management.

4 BIBLIOMETRIC ANALYSIS OF AI IMPLEMENTATION FOR IN-CORE FUEL MANAGEMENT AND RADIOACTIVE WASTE MANAGEMENT

Usage of AI techniques for in-core fuel management and radioactive waste management is a rather narrow field and therefore not an obvious candidate for BA study. The motivation to perform the research despite recommendations given in Table 1 was an article published in 2019 [11] which gives and overview of artificial intelligence applications for in-core fuel management. Several AI methods have been emphasized, including rule-based expert system, neural processing, genetic algorithms, fuzzy techniques, tabu search, cellular automata, simulated annealing, and particle swarms. It is a classical literature review article where the author does not indicate the procedure used to select reviewed articles or the database used as a source. In addition the author focuses review around his own previous work reaching more than 25 self citations thus arousing suspicion in objectivity. As opposed to qualitative character of mentioned review, quantitative character of BA opens possibility for a more objective research and as a supplement which should shed more light into the area of interest. But still one must be aware of the limitations of BA applied to narrow and specific scope. Radioactive waste management represents a broader scope and is therefore a better candidate for BA study.

Based on BA study steps listed in the previous section, the methodology of this research has been defined as follows:

1. Aims: investigate application of AI methods and techniques in the fields of in-core fuel management and radioactive waste management,
2. BA techniques to be used: based on preliminary character of the study it was decided for most common and often used BA techniques to be employed.
3. Procedure for data collecting: Web of Science Core Collection (WoSCC) has been selected as the source database with manual check for duplicates being performed. Several different search terms have been tested for scanning the database due to wide variety of AI methods and techniques generally available as well as non-uniform application of their names. For example, search term "*ALL = (in-core fuel management)*" indicating search for every separate word in the "in-core fuel management" phrase in all of available fields (title, abstract, keywords, etc.) resulted in 244 found records. Search term "*ALL = (in-core fuel management AND ALL = (artificial intelligence)*" indicating combined search for two terms, "in-core fuel management" and "artificial intelligence" in all available fields resulted in only 10 found records. Slight modification leading to search term "*ALL = (in-core fuel management AND (ALL = (artificial intelligence) OR ALL = (genetic))*" resulted in 40 records. Finally applied search term was the following:
   (ALL = (in-core fuel management)) AND (ALL = (artificial intelligence) OR ALL = (genetic) OR ALL = (machine) OR ALL = (neural network) OR ALL = (rule based) OR ALL = (fuzzy logic) OR ALL = (case based) OR ALL = (deep learning))
   It includes most of the AI techniques without going to deep into AI methods. The final search resulted into 63 publications. Manual check up did not reveal any obvious duplicates, and therefore all 63 records have been included in proceeding analysis.
   Similar search term was used for the second area of interest, with just "radioactive waste management" replacing "in-core fuel management". The initial search revealed 380 possible records. No duplicates where found, but a concern was raised by the fact that the records belong to more than 90 WoSCC categories, majority of which containing only one publication. Such diversity and uneven density of publications might have a strong impact on the BA study. Decision was made to hold on to all of the records just to test the BA capabilities.
4. Running BA and reporting results: there are a number of available software packages for performing some or all aspects of BA study. The selected one for this research was

VOSviewer [12], although for basic performance analysis Web of Science tools have been used.

Overall, there are 63 publications in the first analysed field “AI application for in-core fuel management” (AI-incore) that have been cited 833 times (729 times without self-citations), leading to an average of 13.22 citations/publication and h-index equal to 17. In the second field, “AI application for radioactive waste management” (AI-waste), 380 publications have been cited 4773 times (4726 times without self-citations), with an average of 12.56 citations/publication and h-index equal to 34. Graphical distribution of publications and citations over time scale in the fields of AI-incore and AI-waste have been depicted in Figure 4 and Figure 5, respectively.

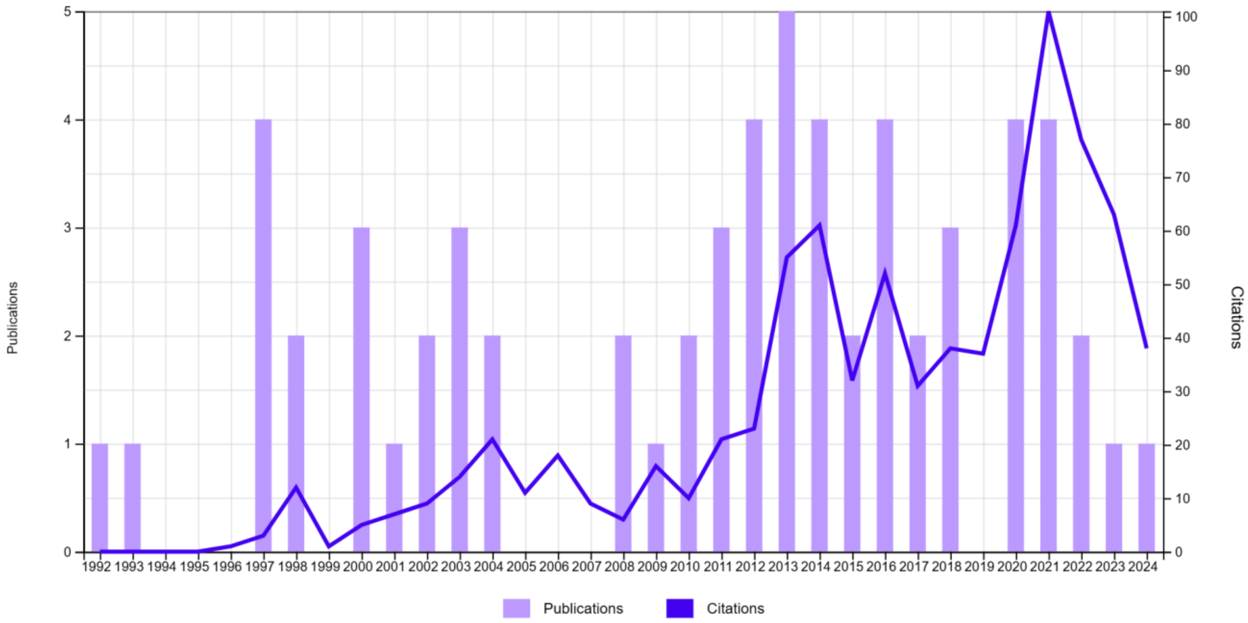

Figure 4: Number of publications and citations for the field AI-incore

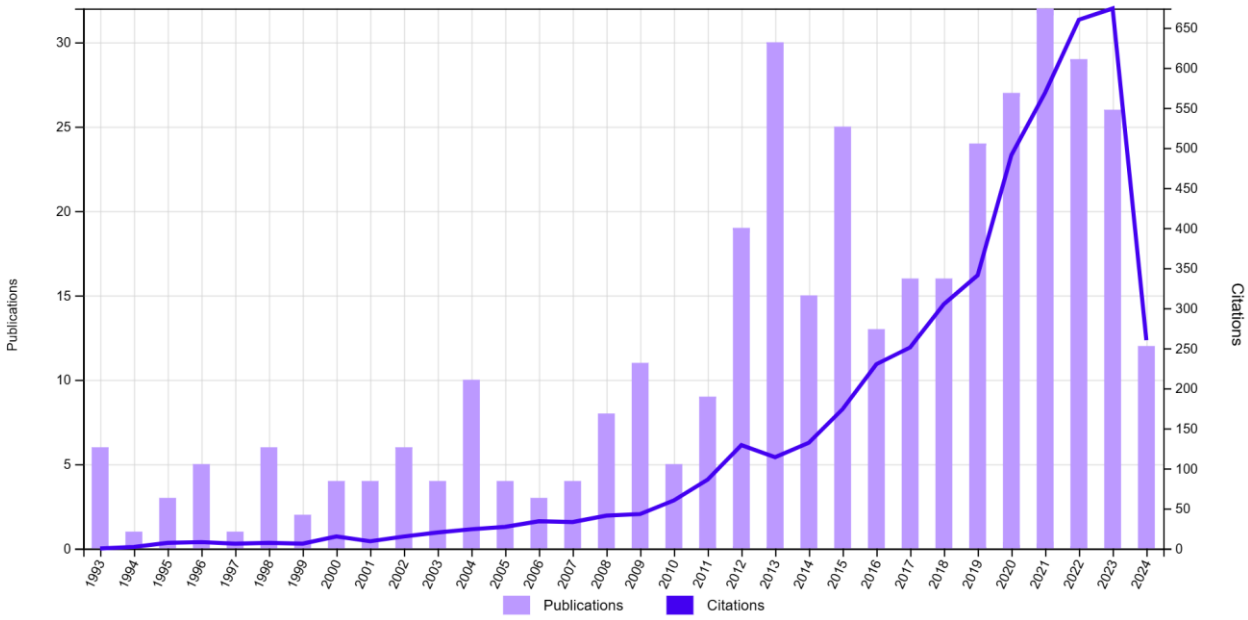

Figure 5: Number of publications and citations for the field AI-waste

Apart from shire difference in numbers of publications, it is also interesting to notice that there is a difference in trends. While number of publications in AI-waste area is increasing over years, in AI-incore area number of publications is very slowly fluctuating with slight decrease noticeable in the last few years.

Co-authorship analysis reveals two stronger collaboration groups in AI-incore area focused around Zolfaghari and Nissan (Figure 6) and a number of collaboration groups in AI-waste field (Figure 7). These AI-waste collaboration groups shown certain level of inter-group collaboration (Figure 8) which can raise research visibility and inspire new ideas.

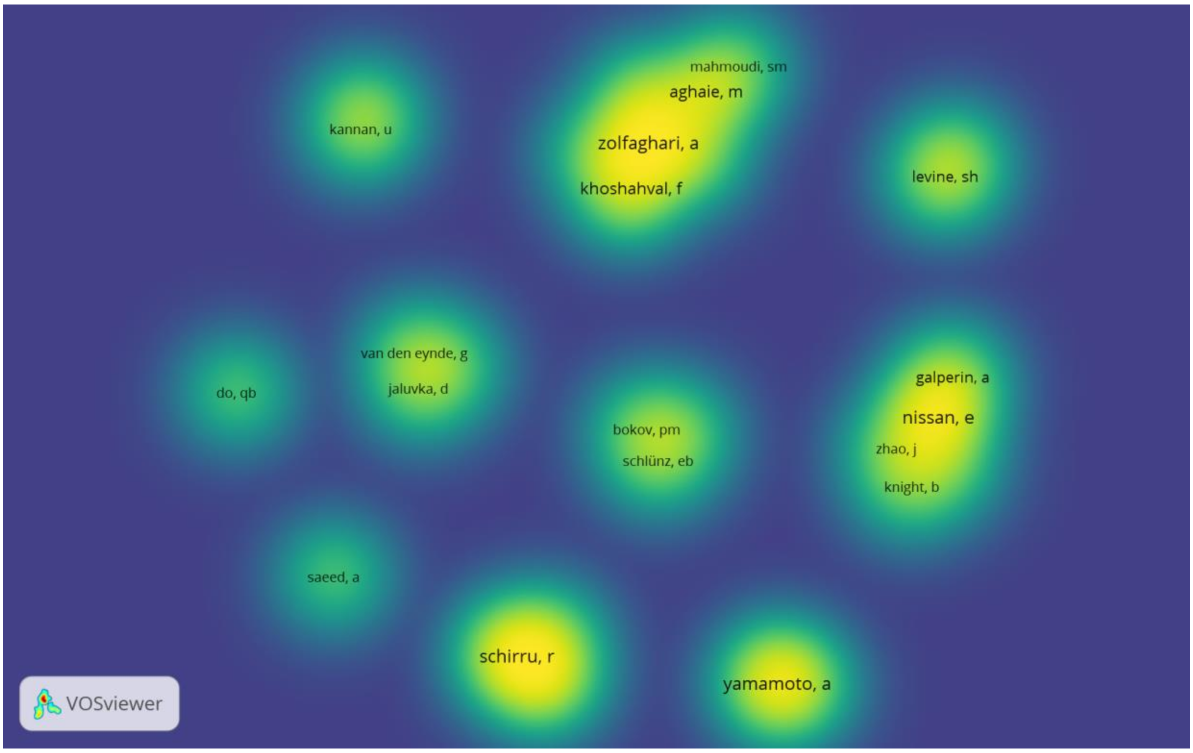

Figure 6: Co-authorship analysis for AI-incore field – density visualization

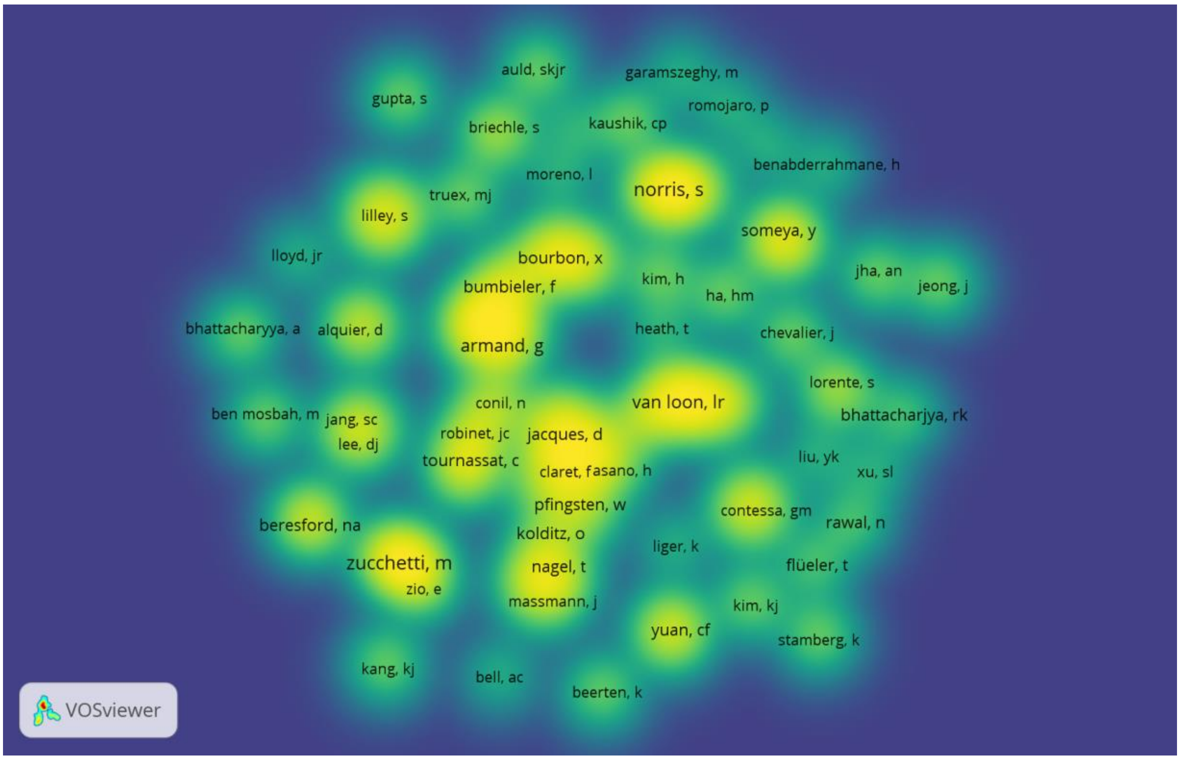

Figure 7: Co-authorship analysis for AI-waste field – density visualization

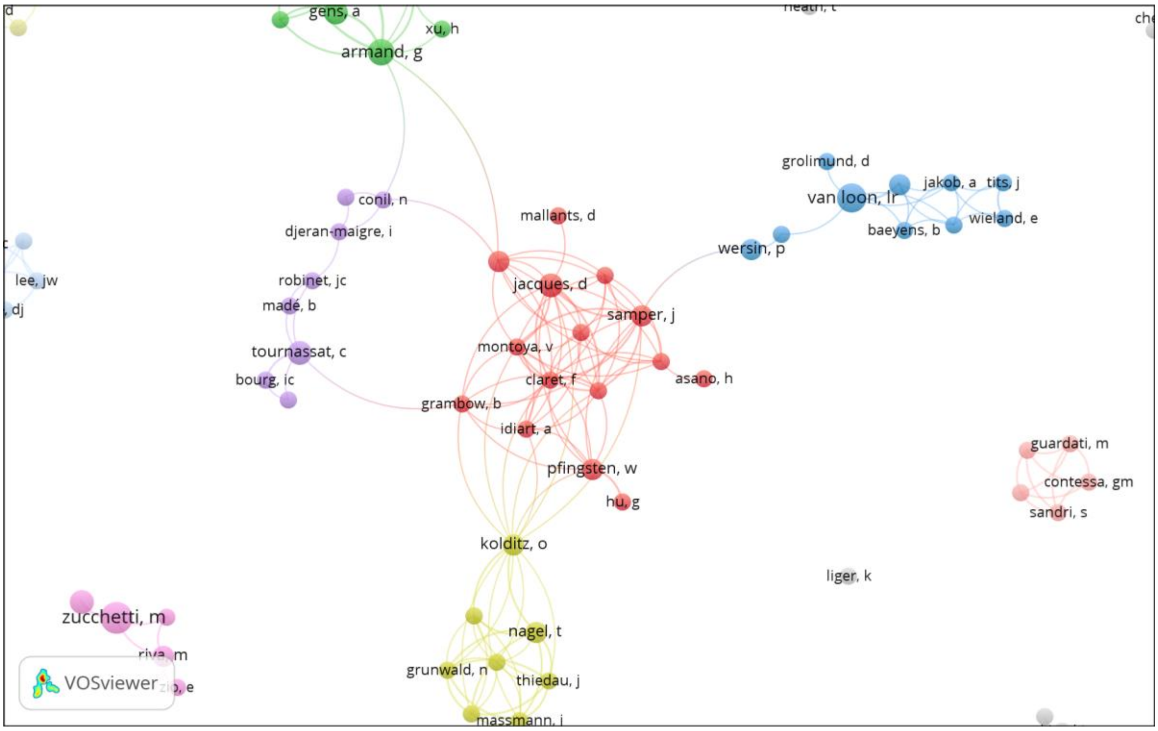

Figure 8: Co-authorship analysis for AI-waste field – network visualization

Another interesting BA technique is keyword co-occurrence. It shows how often particular keywords are used in the area of interest and their correlation to other keywords. Results of keyword co-occurrence analysis for AI-incore field are depicted in Figure 9 where size of the circle indicates frequency of keyword application and lines indicate connection to other keywords (mutual definition in publications). Analysis of these connections can reveal application patterns of separate AI methods or combinations of AI methods. Results of keyword co-occurrence analysis for AI-waste field are depicted in Figure 10.

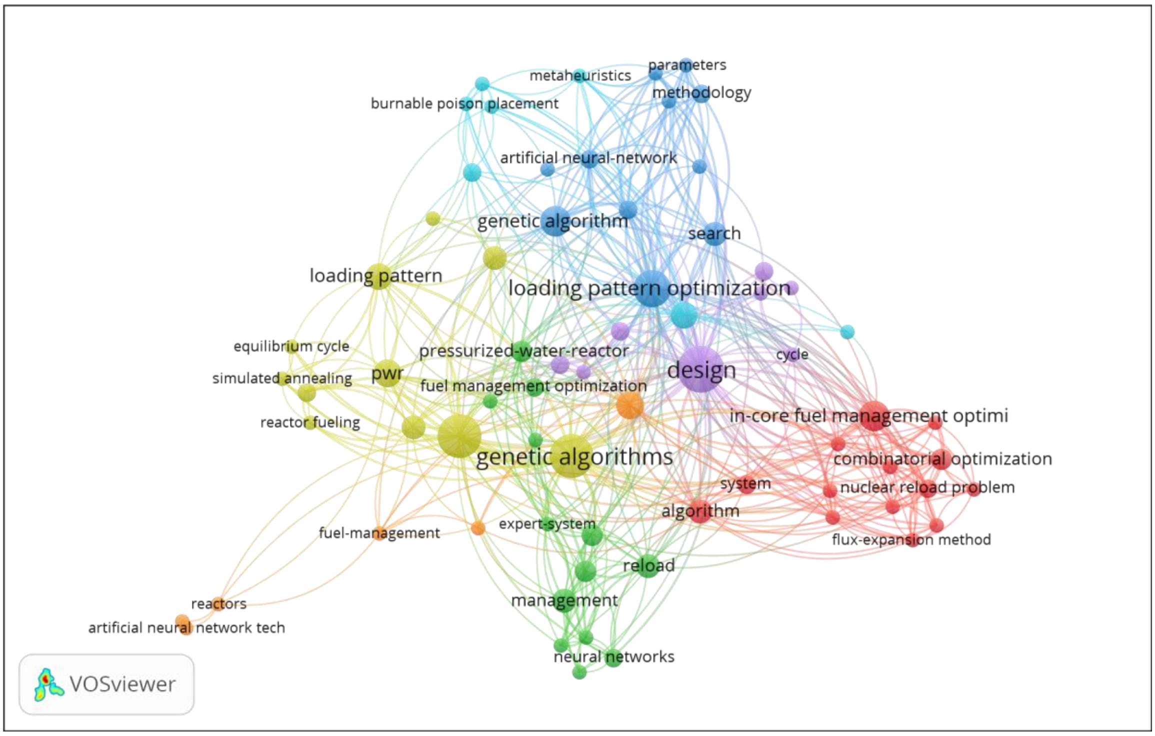

Figure 9: Keyword co-occurrence analysis for AI-incore field – network visualization

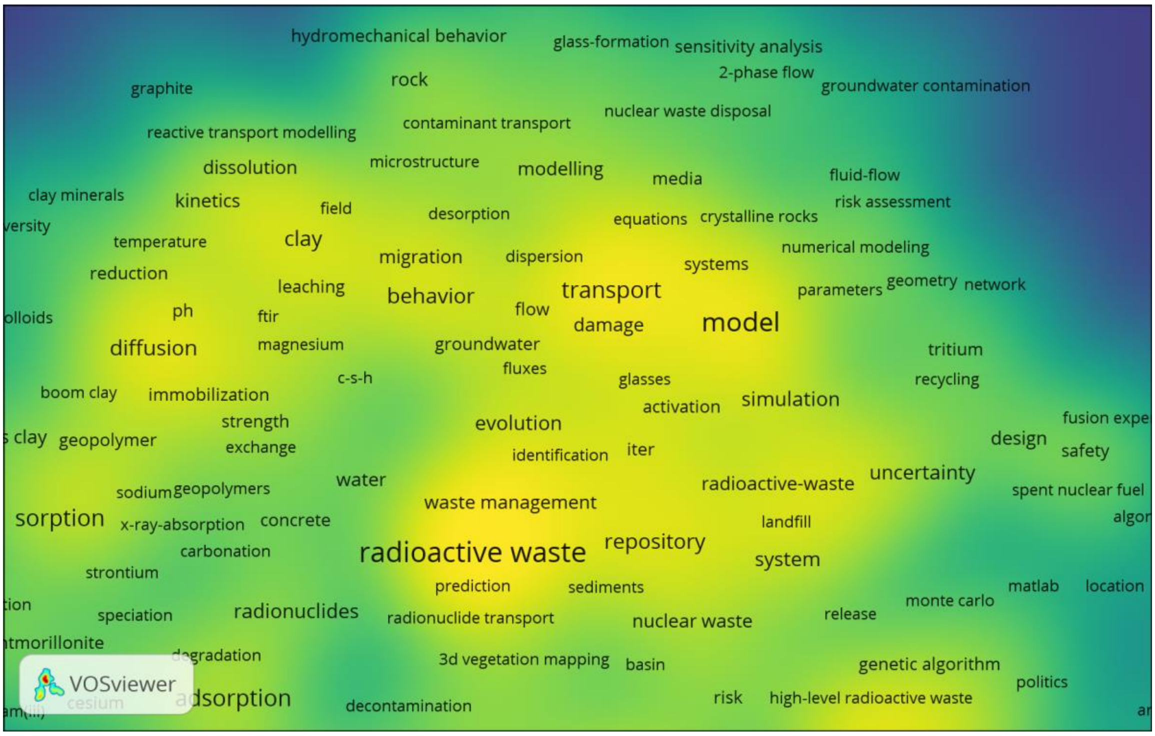

Figure 10: Keyword co-occurrence analysis for AI-waste field – density visualization

Co-word analysis expands previously used co-occurrence analysis by analysing words used in title and abstract. It may help understanding of the patterns and focal points of research published in the analysed articles. As an example, network visualization of the co-word analysis for AI-incore field is depicted in Figure 11. It is evident that *particle swarm optimization* and in-core fuel management optimization (*icfmo*) are very closely related which partially supports Nissan CLR findings [11]. However, it is also noticeable that *fuelcon*, software developed by Nissan is not in the main focal research point in AI-incore field as suggested in [11]

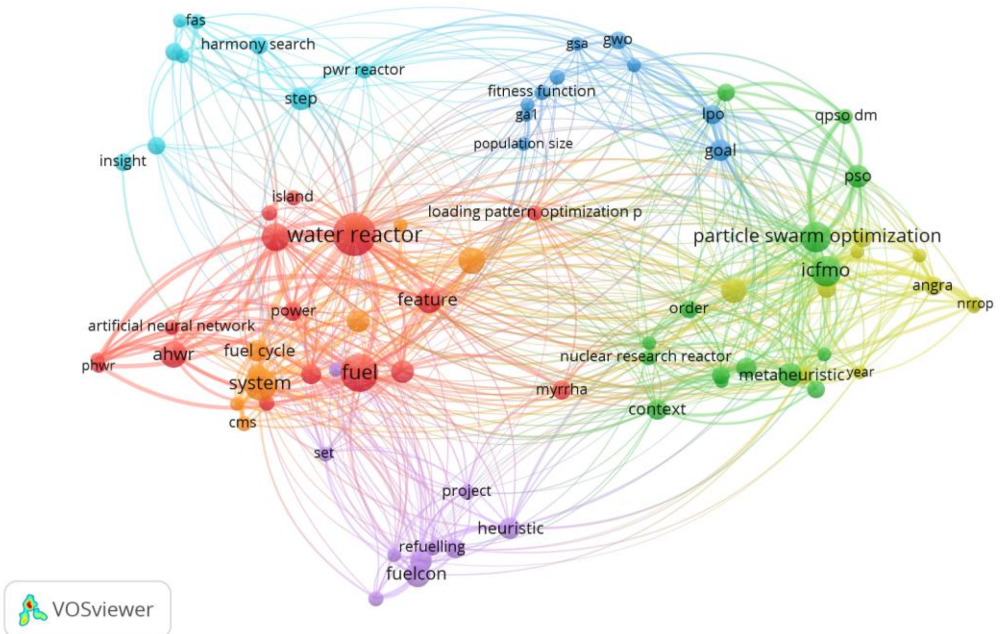

Figure 11: Co-word analysis for AI-incore field – network visualization

5 CONCLUSION

Literature review is an important part of scientific research which enables the researcher to examine the general state of a research field and identify potential gaps to be filled. Growth in the production of scientific knowledge with rapid increase in the number of academic journals, conferences, and other scientific publications, raises the need for rigorous technique to be used for exploring and analysing the literature. There are several review methods, namely systematic literature review, meta-analysis, and bibliometric analysis. Systematic literature review is qualitative in nature, manually performed and suitable for smaller datasets of specific scope. Meta-analysis and bibliometric analysis are generally quantitative methods suitable to handle large datasets and cover wider scope.

The aim of this research was to test whether bibliometric analysis could be used for analysing application of artificial intelligence for in-core fuel management (AI-incore) and radioactive waste management (AI-waste). Both fields are rather specific and not characterised by large datasets and therefore more prone to systematic literature review. At this stage of the research only the most commonly bibliometric analysis techniques have been used.

Preliminary research indicates that bibliometric analysis could be used for review of AI-incore and AI-waste areas as a supplement review tool to enrich the findings of systematic literature review by adding quantitative measure to qualitative assessment. Co-authorship analysis can reveal possible collaboration patterns, keyword co-occurrence analysis indicates patterns of AI methods application, and general focal points of research area can be identified by co-word analysis.

Next step of the research is to implement more enhanced BA techniques to AI-incore and AI-waste fields and also to perform detailed comparison of SLR and BA results attempting to reach combined literature review results for both field. These should be guidelines for our future work in the field of AI implementation to in-core fuel management and radioactive waste management.

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