The social structure of 70 years of literature on Human Reliability

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Abstract

From its first applications to the military domain, HRA progressed to applications in Nuclear Power Plants (NPPs) operations, when development and validation of methods mainly targeted their use in Probabilistic Risk Assessments. In recent years, advances in HRA include the extension to various application fields, the development of new methods or enhancement of existing ones, data collection efforts, among others. These advances are possible due to the increasing number of authors on HRA and collaboration between them. Systematic literature reviews have been increasingly used for understanding various aspects of a research field. While recent reviews have provided an overview of the topics addressed by HRA research, the social structure of the field has not yet been fully explored. This paper discusses the social structure of HRA through 70 years of literature. The review aims at responding to how the links between different authors groups were created, i.e., which large-scale projects, geographical proximity, or research topics contributed to these connections. The results indicate that 1) while the research on HRA was mostly based in the U.S.A. before 2000, China, Japan, and South Korea are significant contributors to the recent literature; 2) despite the increasing diversity of application fields, such as applications to the maritime and offshore industry, the main focus on NPPs operations is persistent since the 1980s; 3) due to large research projects, favored by a connected world, the physical workspace does not limit current collaboration among authors.

Keywords: human reliability analysis, scientometrics, literature review

1. INTRODUCTION

Human Reliability Analysis (HRA) is the discipline that provides methods and tools for qualitatively and quantitatively modeling, analyzing, and predicting human errors in systems in which people have monitoring and control functions. The roots of HRA are in equipment reliability engineering, from which it derives its central concepts and methods [1], [2]. From its first applications to the military domain, focusing on well-defined assembly tasks, HRA progressed to applications in Nuclear Power Plants (NPPs) operations, when development and validation of methods mainly targeted their use in Probabilistic Risk Assessments (PRAs). In recent years, HRA development in other fields such as healthcare (e.g. [3], [4]), process industry (e.g. [5],[6]), and the maritime domain (e.g. [7], [8]) have emerged or been extended. Advances in HRA involve not only the extension to various application fields but also the development of new methods or enhancement of existing ones considering the requirements for advanced HRA methods (e.g. [9]), data collection efforts (e.g. [10], [11],[12]) among others.

Systematic literature reviews have been increasingly used for understanding various aspects of a research field. These aspects include, among others, the main research topics, geographical distribution of publications, and the evolution of the topics and authors throughout time. The reviews aim at providing the reader an accurate picture of the "who, what, when, and where" of the specific research field, allowing for identifying gaps and new frontiers to be explored. Understanding the rapid evolution of HRA research, which evolved from around 20 yearly publications in 2000 to over 150 in 2019 [13], and its current state, trends, and gaps, can highly benefit from systematic literature reviews. Indeed, three recently published literature reviews on HRA aim at providing an overview of different aspects of the field.

Tao et al. [14] present a bibliometric analysis of studies on HRA from 1984 to 2018. The review focuses on identifying the main sources of the papers, the most productive institutions and authors, and a keyword evolution. The authors also provide a simplified overview of co-authorship, limited to presenting a co-authorship map and mentioning the strength of the links. Hou et al. [15] recently published a review of publications from 2009 to 2020, in which they identify research groups based on co-authorship and the main topics addressed by these groups. They also discuss cooperation between institutions and countries and present a simplified co-citation network. Patriarca et al. [13] investigated the intellectual structure of the HRA field through the analysis of over 1200 publications within more than five decades of HRA literature. They identified and thoroughly described the main HRA research areas through a combination of factor analysis, multi-dimensional scaling, and bibliometric mapping. They also discuss the field's evolution through an analysis of the keywords and identify current trends and gaps in HRA research.

This paper aims at complementing the reviews mentioned above with the discussion of a subject not yet fully explored: the social structure of the HRA field. The notion of social structure is used here to capture the relationships among scholars involved in HRA and to understand how they evolved over the years. In scientometrics, social structures are considered critical for understanding relationships in the academic environment and consequently research itself, since it is usually minor institutionally-influenced than imagined [16]. This paper builds on the study conducted by Patriarca et al. [13] and uses co-authorship analyses for identifying Invisible Colleges and their connections. The co-authorship has been chosen as a factor because a more substantial relationship tends to exist between researchers that write together compared to those that cite each other's work, use similar keywords, or attract similar audiences [17]. This paper aims at responding not only to "who" are the main authors within HRA, as attempted by the previously published reviews, but also how the links between different authors groups were created, i.e., which large scale projects, geographical proximity, or research topics contributed to these connections. The study performed in this paper allows thus completing the picture of the research field of HRA, so far offered in more thematic analyses.

2. METHODOLOGY

From a methodological perspective, the scientometrics research dimension used in this paper relies on the one described in [13]. The reference database for the review is Scopus, which represents the largest database of peer-reviewed literature and is relatively balanced among science's technical and social aspects [18]. The methodology makes usage of Scopus data analyzed through VOSviewer, a dedicated software for bibliometric analysis [19].

A search key has been identified to let the query include all papers including in their title, abstract or keywords the words “human reliability” OR “human unreliability”, and indexed in Scopus up to December, 1st 2020.

Due to the focus on the social structure of the field, no additional filters have been set on language or source type. On the same path, the documents obtained from the query (n=2487) have been modelled through dedicated bibliometric maps based on the notion of co-authorship. This notion refers to the 1960s concept of invisible colleges [20]. According to a simple hypothesis, this research assumes co-authorship to be a proxy measure of the social relationships between authors; i.e., the higher the number of co-authored documents is, the stronger the link between two authors.

A co-authorship map was developed through the adoption of a VOS mapping technique. This latter requires a similarity matrix traditionally derived from a normalized co-occurrence matrix (co-occurrence of scholars as authors of the same paper). Rather than using the Jaccard index, VOS mapping adopts association strength as a similarity measure which is a suitable approach in a situation in which many elements need to be included in a map [19]. The association strength between document i-th and j-th (s_{ij}) allows defining a similarity index as follow:

$$s_{ij} = \frac{c_{ij}}{w_i w_j}$$

Where c_{ij} is the number of co-occurrences of items i and j, and $w_i(w_j)$ the total number of occurrences of items i and j. This metric has been reported to be more helpful than traditional multidimensional scaling techniques, especially for a large number of elements [19].

The usage of these metrics allows building the co-authorship maps used to explore the social structure of the HRA research field. In the maps, the bubble size represents the number of documents authored by an author. At the same time, the colors can be (i) either representative of an invisible college or (ii) proportional to the average year of publication of the documents authored by the author themselves.

3. RESULTS AND DISCUSSION

Figure 1 presents the evolution of HRA-related publications throughout time. It is possible to see a first increase in the number of publications around 1979 - the year of the Three Mile Island accident. Indeed, many HRA methods were developed following the accident to respond to the need for risk-informed decision-making, especially through PRA and HRA [21]. The publication of new methods such as SPAR-H, in 2005 [22] and overall popularization of the field explains the continuously increasing number of documents. For the evolution of the keywords used by the authors and topics addressed throughout the time, please refer to Patriarca et al. [13]. Figure 1 also presents the distribution of the documents’ sources. Technical conferences lead as a source for HRA-related publications: over 50% of the papers are published in conference proceedings, closely followed by journal articles. The leading conferences in which HRA research is presented and published are the Probabilistic Safety Assessment and Management Conference (PSAM) and the European Safety and Reliability Conference (ESREL). For journal papers, Reliability Engineering and System Safety (RESS) and Safety Science are the preferred vehicle for sharing research for the HRA authors [13]. Most of the documents are published by authors with affiliation to the United States, as seen in Table 1, followed by Chinese affiliations.

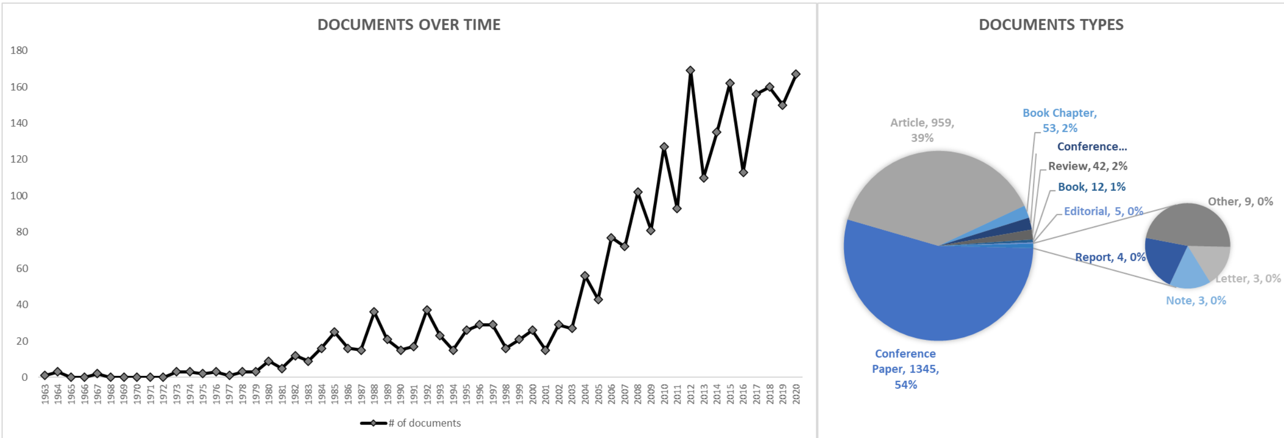

Figure 1: Evolution of HRA publications through time, and sources distribution

Table 1: Countries of affiliations of the authors (only the top 10 are presented)

COUNTRY/TERRITORY	# documents	% documents
United States	667	22.96%
China	330	11.36%
United Kingdom	228	7.85%
South Korea	147	5.06%
Norway	129	4.44%
France	119	4.10%
Italy	114	3.92%
Germany	110	3.79%
Brazil	98	3.37%
Switzerland	96	3.30%

3.1 Invisible Colleges

The results of the co-authorship map are depicted in Figure 2. For clarity, it shows only those authors with at least five documents in the entire dataset, The size of the bubble represents the number of papers authored by an author, while the colors are indicative of different invisible colleges, obtained through VOS mapping technique [19].

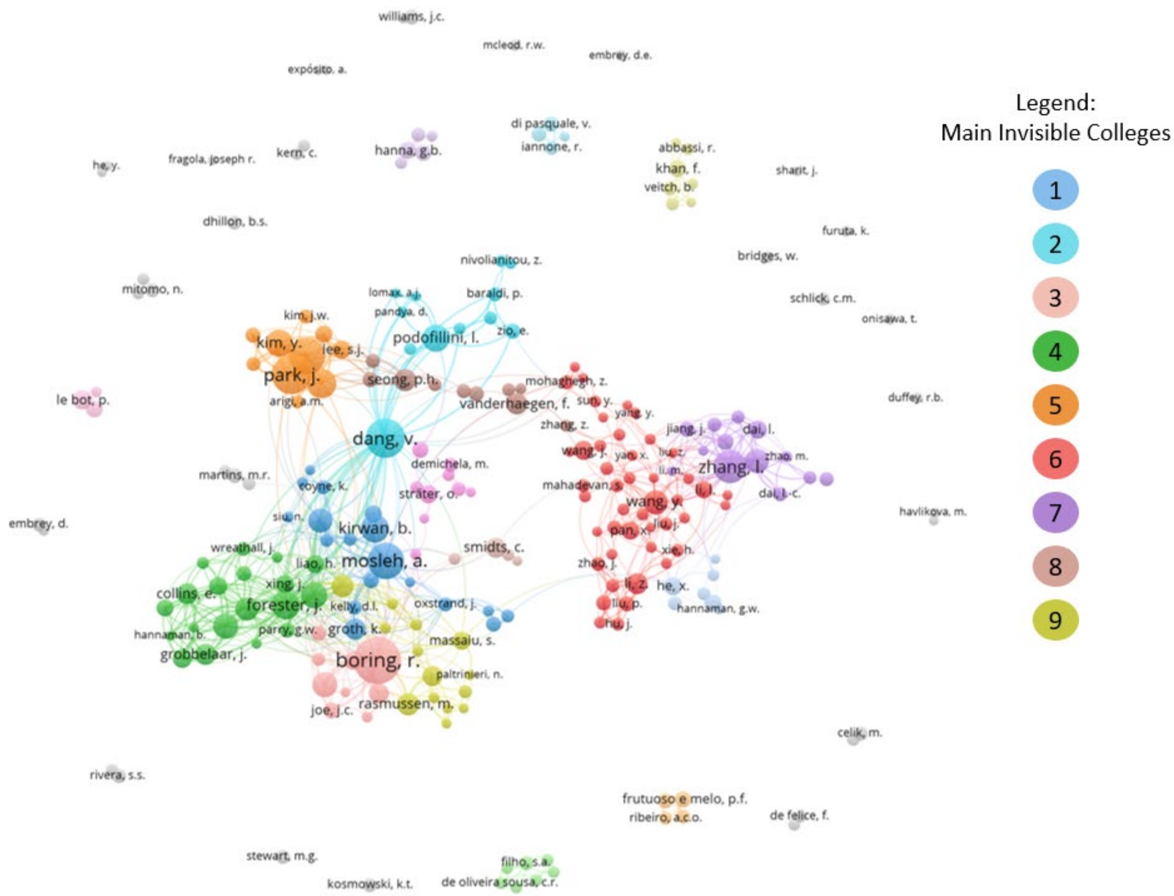

Figure 2: Co-authorship map and Invisible Colleges

An analysis of the co-authorship map can reveal research clusters' – invisible colleges (ICs) - main links and contributions and the relationship between researchers. As expected, common workplaces like research laboratories or universities facilitate collaborations and explain many of the links in Figure 2. In addition, many partnerships are built over large research projects.

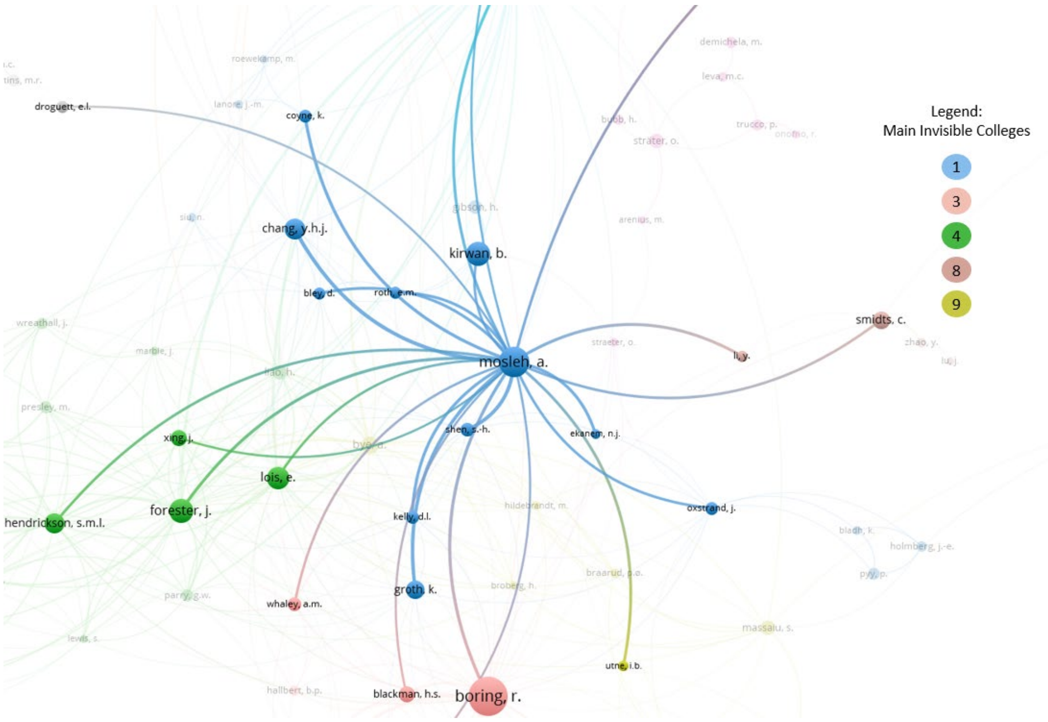

Figure 3: Invisible College 1 and main links

The IC 1 (Figure 3) has A. Mosleh (University of California in Los Angeles, U.S.A.) as a central element. He has collaborative work with several researchers from this and other ICs. Indeed, some of the researchers within this cluster developed their Ph.D. thesis under A. Mosleh's supervision at the University of Maryland – UMD, and continued collaborating afterward. Examples include K. Groth (University of Maryland -UMD), N. Enakem (Chevron), S-H. Shen (NRC), and James Chang (NRC), whose thesis concerned cognitive modeling of operators' performance, resulting in the Information, Decision and Action in a Crew context (IDAC) [23]–[25]. This invisible college leading publications concern model-based HRA, needed for overcoming deficiencies of many HRA methods as discussed by A. Mosleh and J. Chang [26]. In particular, some of the links within the IC 1 and between this IC and others were built over an NRC research project aiming to create a consensus approach to HRA. In addition to A. Mosleh, participants of this project included researchers from this and other clusters, such as R. Boring (IC 3) and J. Forester (Sandia National Laboratories - SNL) (IC 4). This research project was initiated with a workshop of experts in HRA and related domains who identified desirable attributes of a robust HRA method. These attributes include [27], among other, explanatory power ("causal model" for error mechanisms and relation to context, theoretical foundations), ability to cover Human Failure Events dependency and recovery, reproducibility and traceability of the analysis.

Following an assessment of existing methods indicating that none satisfy all of the above criteria, the project aimed at developing a comprehensive HRA qualitative analysis method. The developed framework was presented at the 10th International Probabilistic Safety Assessment & Management Conference (PSAM) in 2010 [27]–[30]. The authors proposed a framework comprising Event Sequence Diagram (ESDs), Fault Trees (FTs), and Bayesian Networks (BNs). The framework continued to be expanded [31], resulting in related works such as the development of PIF hierarchy for use in model-based HRA [32] and a methodology for deriving causal BNs [33] by K. Groth and A. Mosleh. N. Ekanem and A. Mosleh later developed a model-based HRA methodology based on these studies named Phoenix [34]–[36], which uses IDAC as a cognition model of the operators.

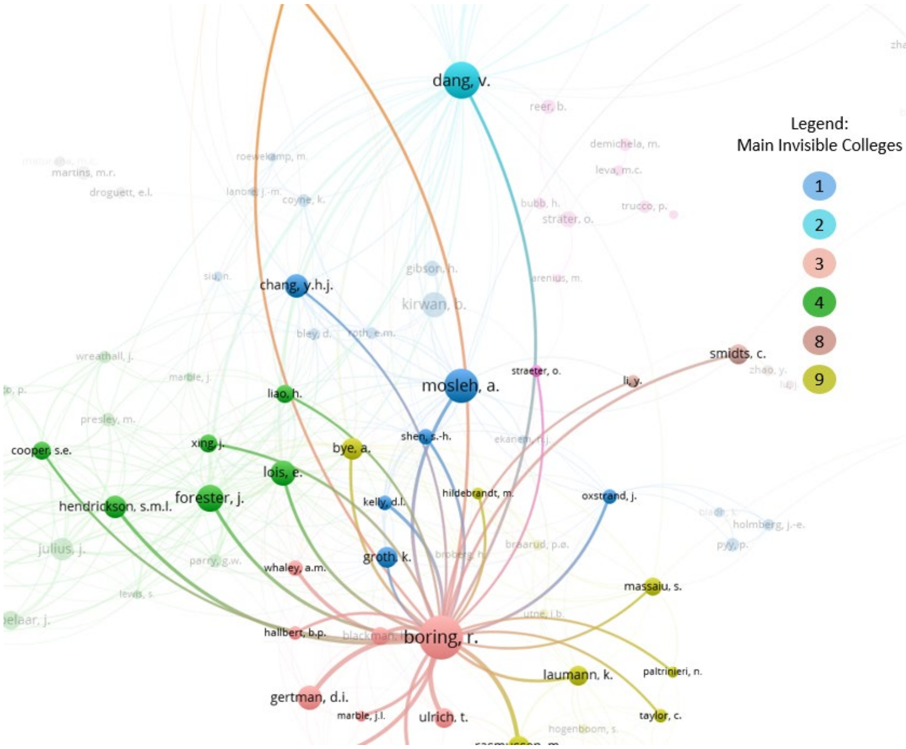

Figure 4: Invisible College 3 and main links

The IC 3 (Figure 4) has R. Boring (Idaho National Laboratory – INL) as one of the central elements, with publications focusing mainly on human factors and HRA [37], [38] and, more recently, the use of simulator data ("microworld") for HRA quantification [39]–[41]. Part of the researchers within this IC also work at INL, e.g., D. Gertman, T. Ulrich, while another part has worked at the laboratory at one point, e.g., A. Whaley. Several connections between this IC and others seen in Figure 4 are rooted at "The International Human Reliability Analysis Empirical Study: Simulator scenarios, data collection, and identification of human failure events", sponsored by the NRC. In addition to R. Boring, participants of this project included J. Forester (SNL) and E. Lois (NRC) (IC 4), S. Massaiu and A. Bye (Institute for Energy Technology- IFE, Norway) (IC 9), and V. Dang (Paul Scherrer Institute - PSI, Switzerland) (IC 2). The project was a multiteam effort supported by the Organization for Economic Cooperation and Development (OECD) Halden Reactor Project, the Swiss Federal Nuclear Safety Inspectorate, the U.S. Electric Power Research Institute, and the NRC. The study aimed at developing an empirically based understanding of the performance, strengths, and weaknesses of different HRA methods used to model human response to accident sequences in probabilistic risk assessments (PRAs). The empirical basis was developed through experiments performed at the Halden Reactor Project HAMMLAB (HAlden huMan-Machine LABoratory) research simulator, with actual crews responding to accident situations similar to those modeled in PRAs. The results were presented in NRC reports and discussed in several papers by the authors [42]–[46]. Among other lessons, the study concluded that [46] (i) the qualitative analysis performed to support HRA quantification is an important contributor to the adequacy of HRA predictions, (ii) the various HRA methods vary significantly in the nature and degree of the qualitative analysis performed, (iii) even the methods with solid guidance for qualitative analysis did not always provide acceptable predictions of HEPs, and (iv) without a good qualitative analysis that covers a comprehensive set of conditions and influencing factors, the methods have an inadequate basis for their predictions. The latter was particularly demonstrated when method applications did not address the cognitive aspects of performance.

More recent links within this cluster are rooted in the project “Analysis of human actions as barriers in major accidents in the petroleum industry, applicability of human reliability analysis methods”. This project led to the Petro-HRA method, an HRA method developed for the petroleum industry built on SPAR-H. The project was a joint effort developed by IFE, the Norwegian University of Science and Technology-NTNU, DNV-GL, SINTEF Technology and Society, INL, and Statoil. The methods, steps, and results of the project were published in several journals and conferences [5], [47]–[50]. Researchers as M. Rasmussen and K. Laumann (NTNU) (IC 9) and C. Taylor (IFE) (IC 9) were part of this project.

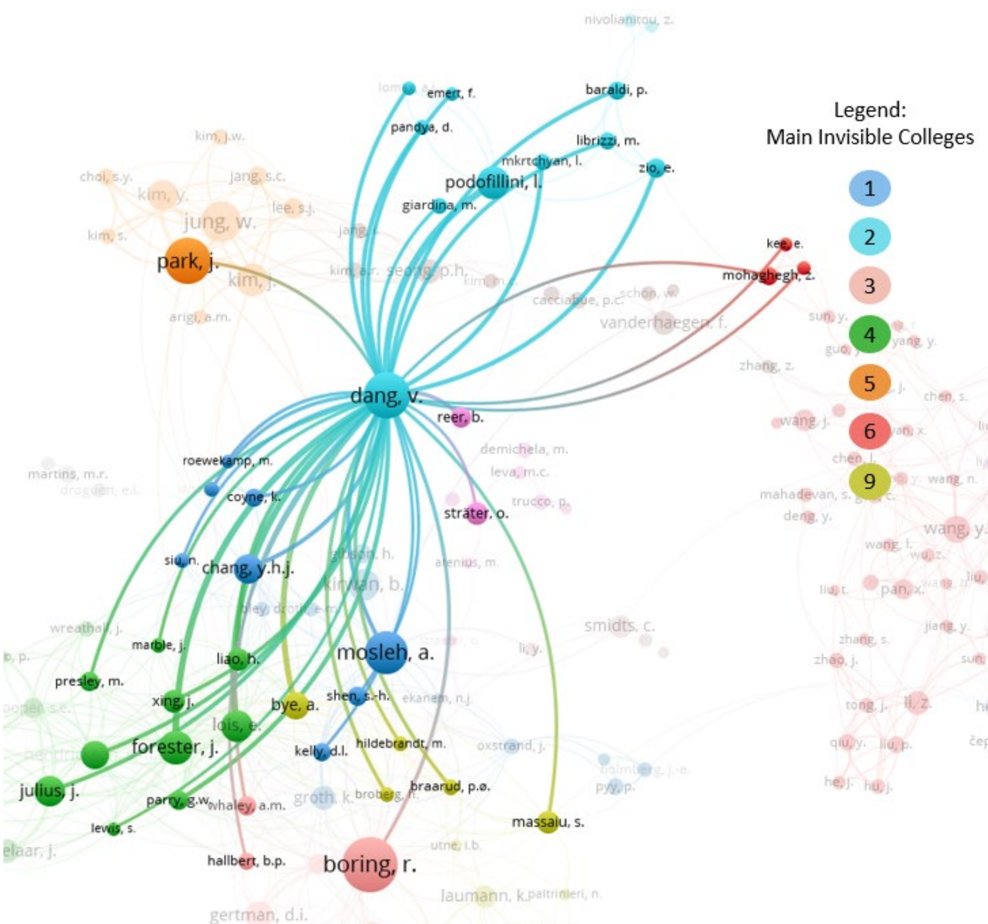

Figure 5: Invisible College 2 and main links

As discussed above, V. Dang, the central element of IC 2, has collaborated on the International HRA project and research related to model-based HRA framework, building most of his links to other clusters. In addition to those projects, his research, along with others within this same IC, e.g., L. Podofilini (PSI), comprises BNs, fuzzy expert systems, and uncertainty in HRA [51]–[53]. In this same main topic, they collaborate with researchers from the Polytechnic of Milan, such as E.Zio and P. Baraldi, also pertaining to this IC [54], [55]. These collaborations were facilitated by the common link of the Polytechnic of Milan, where M. Librizzi concluded his Ph.D. and L. Podofillini under E. Zio's supervision, and where P. Baraldi is currently a professor. V. Dang has also built collaborations with J. Park (Korea Atomic Energy Research Institute (KAERI), Republic of Korea), the central element of IC 5, on data collection methods [56].

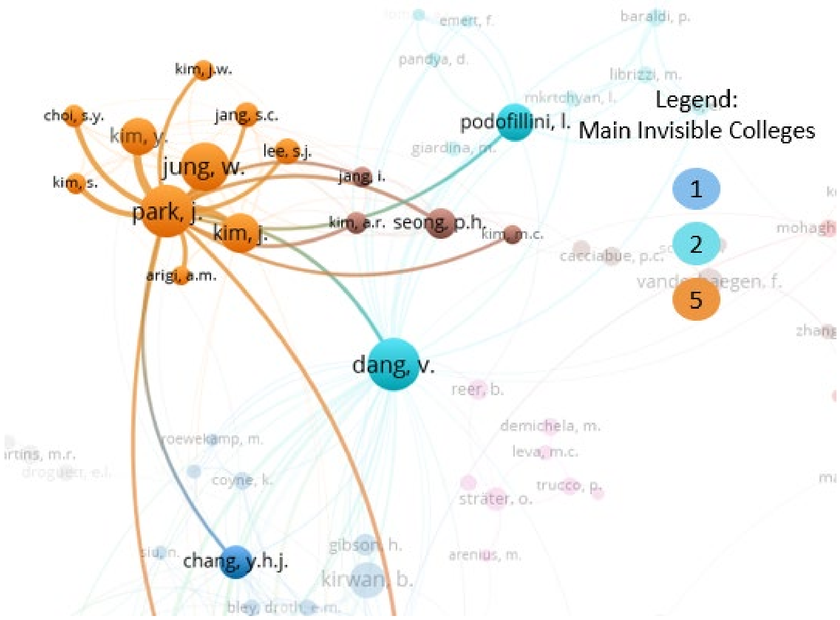

Figure 6: Invisible College 5 and main links

The contributions within IC 5 have a primary focus on data collection for HRA (e.g [56], [57]). Recent research has focused on human reliability data extraction (HuREX), a framework developed by KAERI for data collection and analyses from a simulator to generate HRA data, as well as in advanced NPP main control rooms [58]–[62]. HuREX provides guidance on the identification of unsafe acts (UA) and the processing of collected data. In addition, it allows analyzing collected data based on the associated forms and taxonomy on generic task types and error modes. A recent application study using two sets of full-scope training simulator records quantified 37 HEPs for 21 generic task types [61].

HuREX is not the sole effort for data collection for HRA using simulator data. Indeed, recent collaborations between KAERI and the NRC, through J. Chang (IC 1) are built over shared experience with simulator data collection. The SACADA project (Scenario Authoring, Characterization, and Debriefing Application) was developed by the NRC to collect data needed in HRA from nuclear power plants' operator training, in which also collaborates B. Kirwan (Eurocontrol, France) and other researchers of IC 1. Since 2012, the SACADA system has been implemented in a US nuclear power station and a research institute to collect their operator performance data in simulator exercises. Some nuclear power stations are piloting the SACADA system to decide whether to routinely use the system in their operator training programs [10], [63].

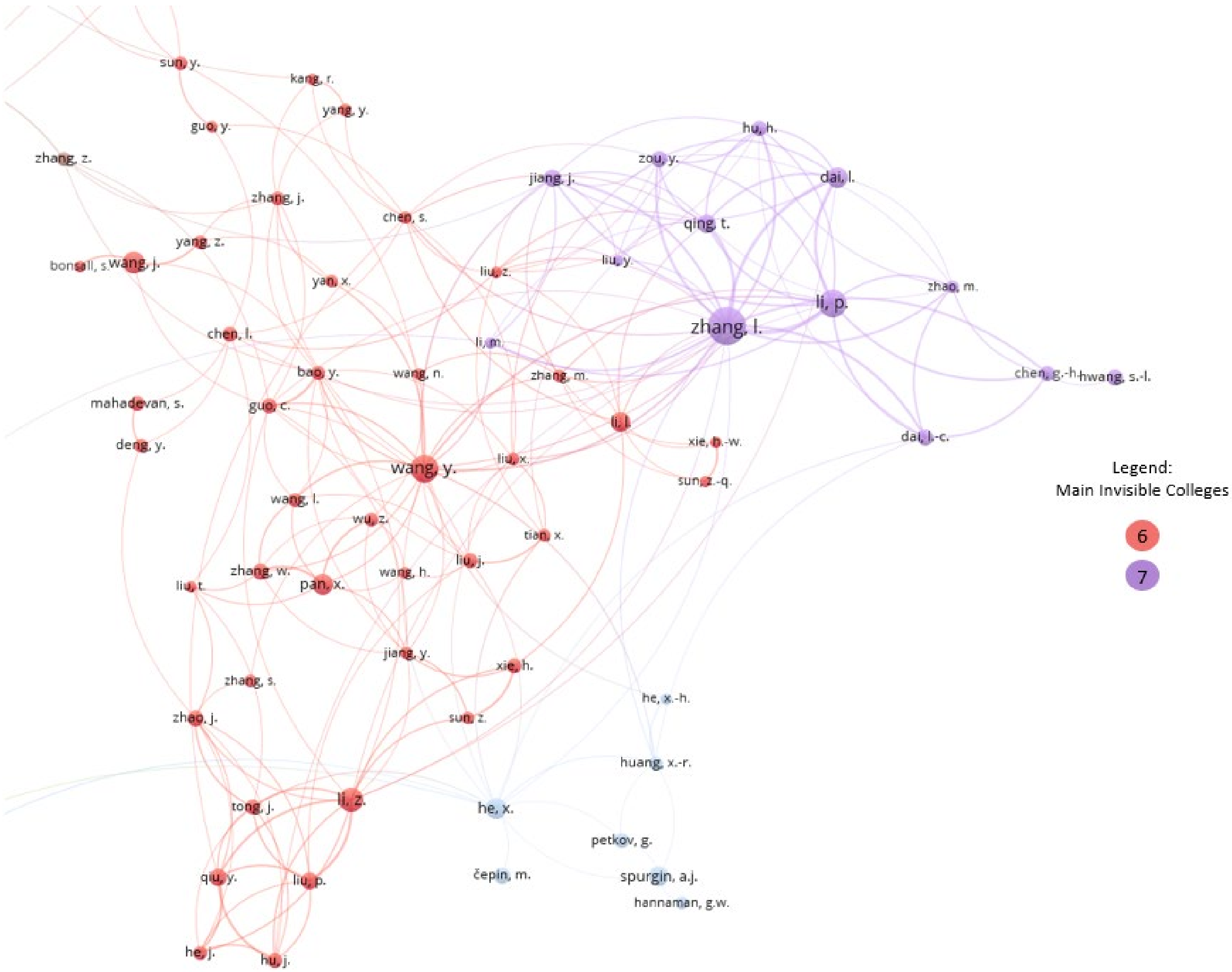

Figure 7: Invisible Colleges 6 and 7

The invisible colleges on the right side of Figure 2 comprise researchers located mainly in Asian institutes and universities (Figure 7). IC 6 main elements are located in China, such as Y. Wang (Northwestern Polytechnical University) and Z. Li (Tsinghua University). This IC research has a focus on digital NPPs [64], [65], as well as HRA applied to maritime operations [66], [67]. IC 7 authors are also mainly located in China, such as L. Zhang (University of South China) and P. Li (University of South China). This cluster research resides primarily on NPPs, also contributing to the analysis of recent digitalization of NPPs [68], [69].

Additional authors can be grouped into smaller invisible colleges, with no strong collaboration with others clusters ("isolated clusters"), such as M. Martins and M. Maturana (University of São Paulo, Brazil), whose focus mainly on maritime applications [70], and F. Khan (Memorial University of Newfoundland, Canada), with an emphasis on offshore applications [71], [72].

3.2 Evolution of the social structure

In addition to the observations of the section above, a similar bibliometric map can be explored in terms of average "publication age". Figure 8 presents a map in which the color of the bubbles referring to each author depicts the average year of publication of the documents authored by the author themselves.

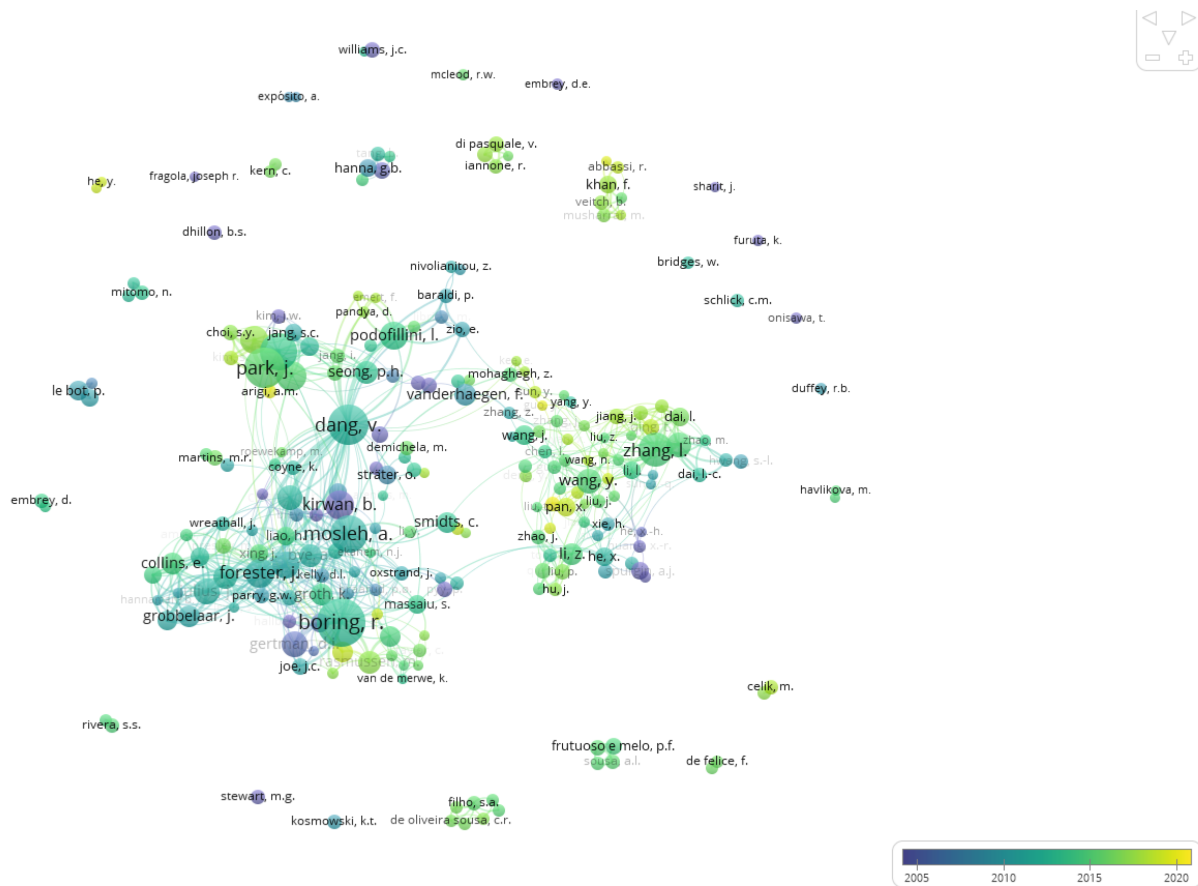

Figure 8: Co-authorship map according to the average year of publications.

Some authors who provided the foundations of the discipline, such as Kirwan and Gertman, have publications dating from before 1990. As such, the average year of their publications is low, which does not necessarily mean that they do not have more recent contributions.

It can be seen that the clusters in the right (IC 6 ad 7) present an interesting mix between researchers with mainly recent publications (2014-2016) and researchers with a lower average age of works. This represents an expected result of the investment of these countries' in research, in particular in the Nuclear industry. The growing number of their contributions in the field leverages from partnering with well-established researchers of the field (with a lower average year of contribution). Most of the isolated clusters include researchers with mainly recent publications, in some cases not leveraging from collaboration with established authors. The main links of some clusters, such as Boring, Mosleh, and Dang, have a "medium" average year of publications. In addition to contributing to the foundations of the discipline, those authors continue to collaborate with young researchers and maintain a considerable number of recent publications.

The evolution of the number in HRA publications can be marked by two years, as illustrated in Figure 1: 1980, and 2000. The earlier HRA publications, before 1980 (Figure 9), focus mainly on NPPs operations. This era was marked by the WASH-1400 - Reactor Safety Study, the first full-scope use of PRA techniques, published 1975 [73]. THERP was developed in its earlier version in 1975 by A. Swain and H. Guttman [74] (depicted in the red cluster). Swain and Guttman's collaborations with others of this cluster, such as J. Fragola, L. Hanes, and J. Sullivan, concern mainly situation analysis applied to nuclear safety [75]. Other clusters or individual authors of this era also discussed HRA for other fields. D. Embrey, for instance, has discussed human errors in the chemical industry and other industrial systems [76], [77], and N. Cole and E. Cooke have discussed human performance within the medical field [78].

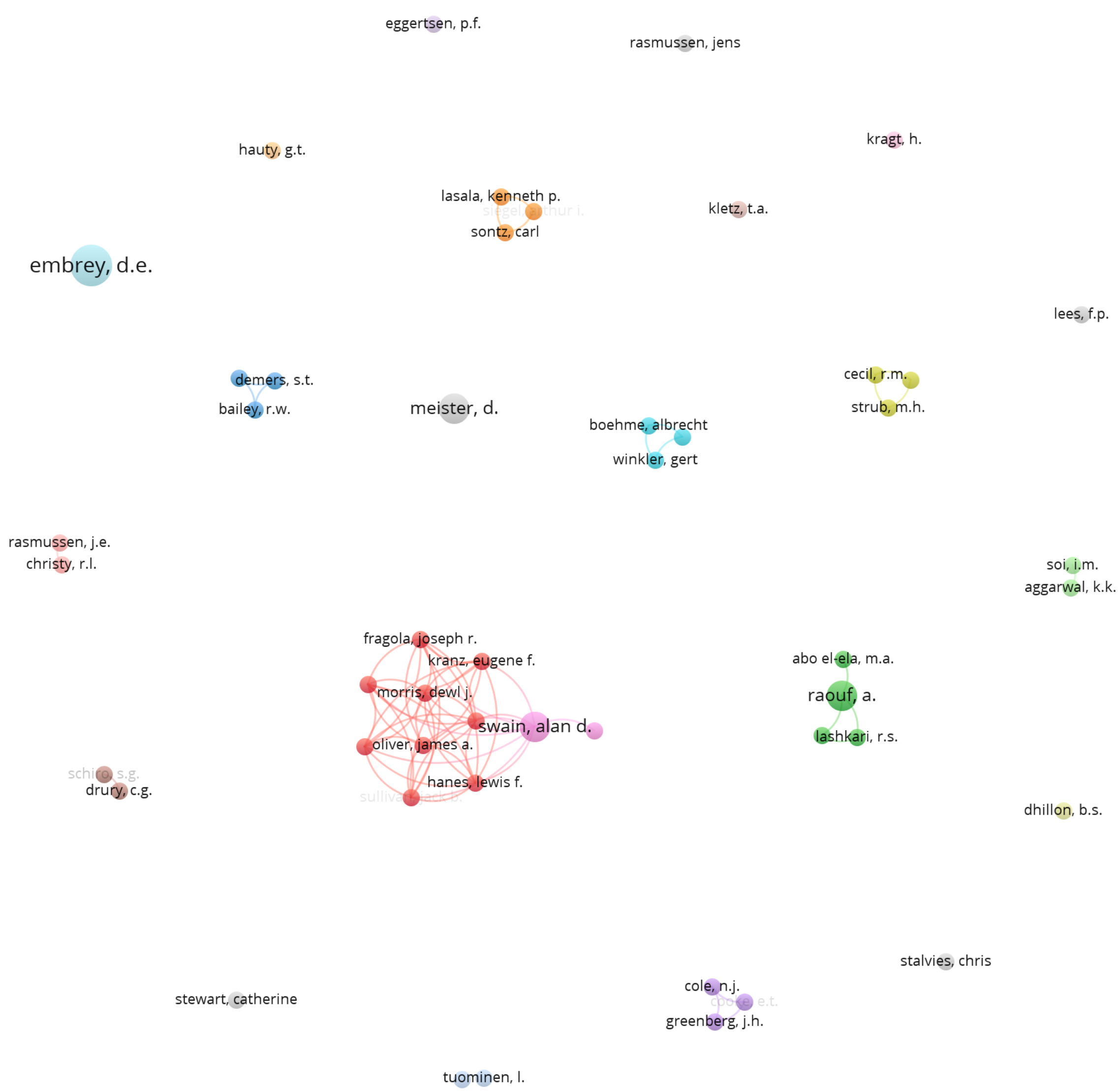

Figure 9: HRA Pioneers: co-authorship map – before 1980

The number of authors researching HRA has significantly increased between 1980 and 2000, as presented in Figure 10[1]. Some authors from the pre-1980 literature continued to contribute to HRA throughout the years. Embrey developed the methods Systematic Human Error Reduction and Prediction Approach (SHERPA), and Success Likelihood Index Methodology (SLIM) [79] in 1986. Swain and Gutman enhanced

[1] Only authors with two or more papers in the field are presented in the figure for better visualization.

THERP, formally published by the US NRC in 1983 [80]. As a consequence of the Three Mile Island (TMI) accident, many authors between 1980 and 2000 focused on NPP safety, especially in the U.S.A., sponsored by US NRC projects. As many methods were developed within this period, comparison and validation of these methods became necessary. B. Kirwan conducted many of these studies [81]–[84], focusing on NPP. Most of the authors included in Figure 10 were based in the U.S. in that period. Yet, this era is also marked by the appearance of authors based in Japan, such as Y. Murayama (Ship Research Institute), and H. Yoshikawa (Kyoto University).

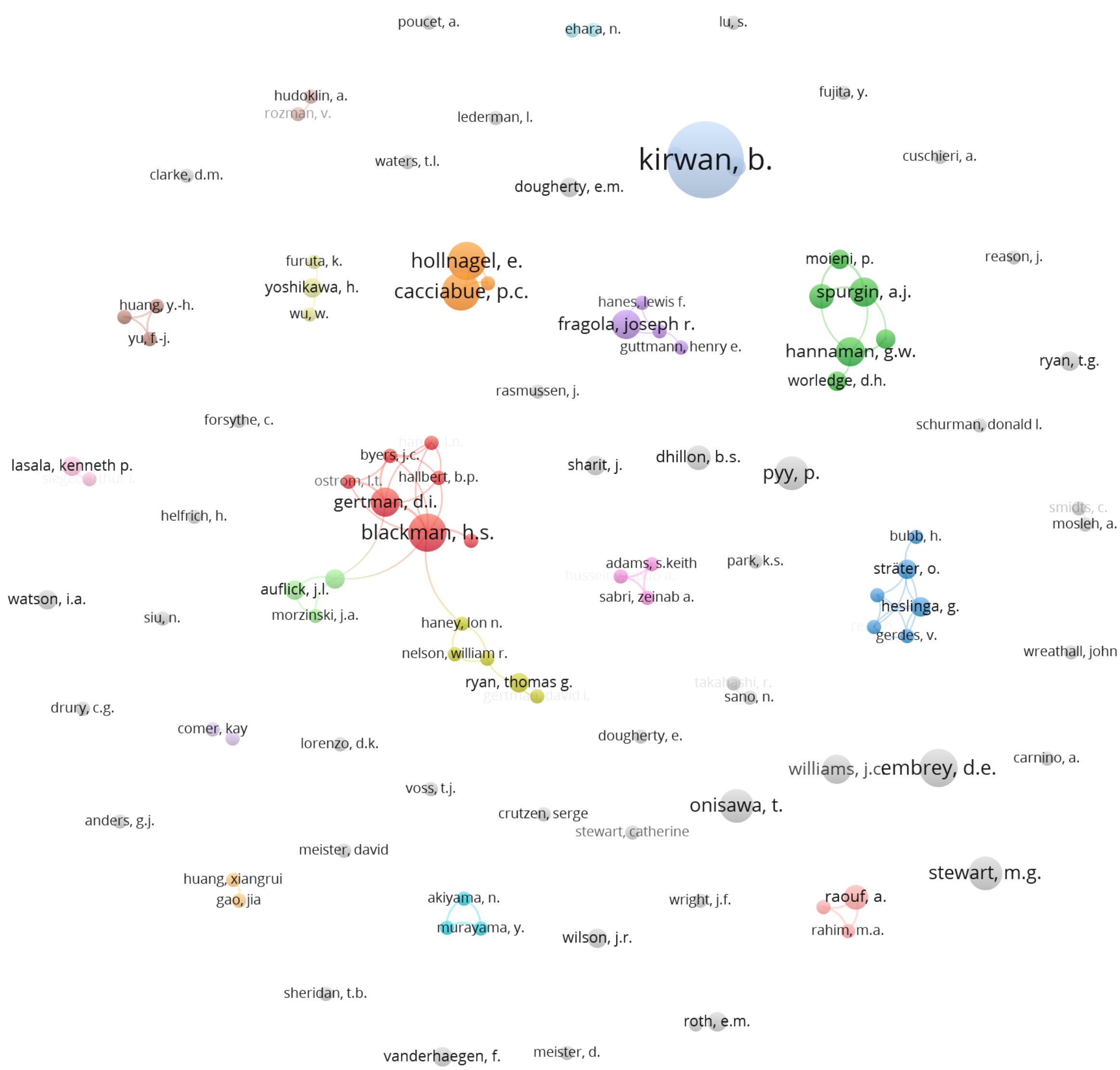

Figure 10: HRA founders: Co-authorship map – from 1980 to 2000

From 2000 to the present day (Figure 2), many invisible colleges appeared, and many more links between them were established. Naturally, some prominent authors from the before-2000 era did not continue to contribute to the HRA field at the same pace, such as Embrey (Figure 8). Others, such as Kirwan, continued active in the field, collaborating with recent efforts such as data collection [10], [85].

The 2000-2021 era marks the consolidation of authors of Korean and Chinese affiliation in the HRA field – the latter currently responsible for the second larger number of HRA publications (Table 1). It also marks the increase in links between ICs through large international projects. The increasing accessibility to international voyages and use of technology for long-distance communication enabled collaborations that cross geographical borders.

4. CONCLUDING THOUGHTS

This paper complements recent reviews of the HRA research through a focus on the social structure of the field. The description of the links between authors of the same invisible college and between different invisible colleges is limited to public information on large-scale projects, geographical locations, and additional information such as links established through thesis' supervisions. Some of this information is not public or easily found for all the invisible colleges. While the description of some links leveraged this paper authors' knowledge of HRA researchers, not all links and invisible colleges could be described in the same level of detail.

The identified invisible colleges confirm that common workplaces as research laboratories or universities orbiting around a prominent researcher or large projects with multinational, multiteam effort facilitate the creation of expertise specialized on HRA. R. Boring, A. Mosleh, J. Chang, V. Dang and J. Park are only some of the authors leading the identified invisible colleges. HAMMLAB, SACADA, HuREX and Petro-HRA are examples of relevant projects that delivered important contributions to HRA through them. Some of these contributions led to a relatively recent increase of publications from the invisible colleges in South Korea and China, which has shifted the barycenter of the HRA community towards the East. These extensive research projects have also been successfully connecting researchers from different institutes and countries. Clusters mainly composed of researchers with recent publications have been leveraging from collaborations with well-established researchers, which can lead to positive results in their contributions. As some institutes/universities are relatively isolated geographically, researchers from these areas benefit from the involvement in large research projects and can, in turn, start further collaborations.

In addition to the expected increase of the number of authors throughout the time, the following can be observed when comparing the co-authorship maps from before 1980, 1980-2000, and from the complete literature until the present day (Figure 2). First, while the research on HRA was primarily based in the U.S.A. before 2000, China, Japan, and South Korea are key contributors to the recent literature. Second, despite the increasing diversity of application fields, such as applications to the maritime and offshore industry, the main focus on NPPs operations is persistent since the 1980s. Finally, due to large research projects favored by a connected world, current collaboration among authors is not limited by the physical workspace.

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