A pipeline for AI-based quantitative studies of science enhanced by crowdsourced inferential modelling

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Abstract. Interdisciplinary research efforts in human-powered artificial intelligence (AI) algorithms have contributed to reveal hidden relationships and properties across knowledge graphs. However, the expanding scientific landscape presents challenges in capturing knowledge flows and their impact accurately. For a long time, scholars have made progress in the quantitative analysis of science indicators, historical footprints, and network dynamics. Despite the remarkable strides over the last decade, the pipeline underlying the measurement of scientific output is still difficult to execute in a fully automated way. To overcome these challenges, several academics and practitioners have increasingly explored hybrid intelligent systems that combine machine learning (ML) and crowd-based processing in data-driven research as an instrument of science policy. Building upon these promising advancements, this paper proposes a reinforcement learning from human feedback (RLHF) approach, offering insights for implementing hybrid crowd-algorithmic systems intended to support research evaluation and decision-making. The authors argue that an AI-based RLHF system pipeline can greatly benefit science stakeholders worldwide by enabling new forms of human-AI interactive and continuous sensemaking.

Keywords: Crowd-machine processing · Human-AI interaction · Hybrid intelligent systems · Knowledge graphs · Quantitative studies of science · Reinforcement learning · RLHF · Scientometrics

1 Introduction and Motivation

Improving the way scientific activity is measured has many direct and indirect impacts on the practice of science across all disciplines. Sharing a broader commitment to the study and analysis of technological progress and science at large, scientometrics rests upon a full-fledged, well-established and problem-oriented program dedicated to the understanding of "*the formal and semantic aspects of the scientific literature*" [1]. This includes citation-level assessments of specialties and disciplines, distributions of knowledge production using institutions and regions as the main units of measurement, relations among variables like research funding and scientific collaboration, among many other ways of quantifying scientific activity and mapping its underlying characteristics [2]. In connection, there is a remarkable increase in the number of publications per year and this cumulative growth is posing new challenges to all parties involved and affected by research production and evaluation such as government and industrial research laboratories, universities, and funding agencies. Despite the growth in the development of artificial intelligence (AI)-based technologies, current algorithms involve expensive training and are usually prone to errors and hallucination, failing to capture complex knowledge representations that may range from matrices of similarity between topics to the early detection of technology threats based on overlapping words [3]. To overcome these issues, we propose a human-AI interactive pipeline augmented with scientometric capabilities where the AI-driven decision-making and interpretation processes are iteratively complemented by human inputs, enabling "*more user interaction in the automated reasoning process*" [4] and thus reducing the risk of database inconsistency and erroneous data inferences.

At its core level, the proposed system integrates bibliometric-enhanced information retrieval (IR) and crowdsourced inferential modelling into a reinforcement learning from human feedback (RLHF) model designed to support the multidimensional representation of science entities and dynamics [5]. Motivated by the recent advances in human-AI interaction, we propose a multi-modular system approach that relies on expert and crowd contributions that are then leveraged to model the system behavior. We believe that a hybrid intelligent approach enables a more differentiated understanding of scientific facts through meaningful categorizations and descriptive statistics that can be correlated and then explored using faceted search. Thus, the main contribution of this study lies in the characterization of the system pipeline, following the typical design science research (DSR) phases that end up with a qualitative evaluation to validate the proposal's feasibility.

2 DSR Methodology

Following problem exploration oriented to the infrastructural aspects needed to support scientometric analyses, a DSR approach was applied taking into account the procedural steps from Peffers and co-authors [6]. As a form of applied research aimed at developing purposeful artifacts (either technological or not), this design-oriented and artifact-centric approach has been successfully adopted in an extensive range of domains. Similarly to other in-progress research projects described in the literature (e.g., [7]), our problem formulation was inspired by the difficulty of getting fine-grained data structures able to match particular research questions and search needs when dealing with the particularities of scientometric studies. That is, obtaining broad-scale multidisciplinary views from different knowledge representations is critical in the current data-intensive science era, as many stakeholders increasingly need to take critical decisions (e.g., funding allocation) and remain aware of the developments across disparate fields. Moreover, some bibliometric IR problems such as information overload and vocabulary mismatch still persist today. Consequently, we need to develop alternative ways of computationally modelling scientometric processes with the aim of providing comprehensive depictions of scientific activity [8]. In this sense, our main goal is to create an innovative artifact to address the problem outlined above. The problem identification was informed by a series of scientometric studies conducted over the span of a decade (e.g., [2, 9]). This ground work served as a starting point to identify a set of design requirements (DR) that were then adapted to the context in which the system will be used. Next, a set of design principles and features were established to furnish guidance and orientation for the design in compliance with Möller et al.'s [10] method for design principle development.

3 Initial Requirements, Design Principles, and End-users' Intention towards Use

A paradigmatic approach that we assume to be particularly important for the design and deployment of a crowd-algorithmic scientometrics-based data analysis system involves the consideration of technological artifacts and socially situated practices (e.g., goal-directed collective activities intended to create metaknowledge) as fundamental units of research [11]. From a data engineering perspective, the diversified array of views provided by crowds allows a multi-level observation of the structure and changes of scientific and technology fields.

3.1 Design Issues, Architectural Components, and Implementation Details

During the first design cycle of our DSR project, we implemented a scientometric approach operating in an open participation model to support experts and the general public in contributing to the improvement of data quality. At the most basic level, the SciCrowd system [8] enables data crawling and indexing so that scientometric data can be easily deconstructed and assessed within the knowledge graph. This is done using a bibliometric-enhanced IR model through which entities (e.g., authors, institutions) and metrics (e.g., citations) are extracted and made accessible in the database for further exploration and analysis. Therefore, we grounded our approach on a hybrid human-AI scientific information extraction pipeline [12]. In such a model, the data is automatically crawled from public sources and then modified (or even added) manually by users. Regarding the relationships that can coexist among linked entities in the knowledge graph, there is also a need to integrate multiple data sources and ensure interoperability for semantic linkages [13]. Simultaneously, user interactions with data can contribute to the continuous improvement of the database in a hybrid fashion by training the algorithm on these interactions (e.g., deduplication for cases where there are similar entries in the database) and predicting future actions based on similar occurrences. Since our research is in the specific context of bibliometric-enhanced IR, these efforts are supported by an interactive pipeline for aiding human-AI decision-making during the content and context enrichment for quantitative and qualitative modelling.

As Lahav and associates [14] noted in a recent study, faceted navigation is particularly relevant for enhancing information seeking and scientific knowledge discovery practices. This emphasizes the importance of developing filtering mechanisms capable of dynamically specifying and refining concepts, taxonomies, and other ontological conceptions through a tailored explanation of entities and relationships. Expanding upon this, such concepts and semantic linkages can be coupled with traditional bibliometric indicators and alternative metrics (altmetrics) to measure aggregate evolution patterns and other characteristics of quantitative studies of science.

Given the demonstrated value of crowdsourcing in other domains, the scientometric processes supported by the SciCrowd system can be further decomposed into independent chunks of human intelligence tasks (HITs) [15]. In the simplest case, the stigmergic editing form of classification supported by our proposed system pipeline enables each contributor to build on one another's input implicitly [16]. In such arrangements, a crowd can contain static and dynamic properties (e.g., location, motivation) that are inherent to the behavior of their constituent members. In order to support crowd participation and authorize users to edit, delete, and add entries in a flexible manner, we implemented a set of authentication and revocation mechanisms capable of differentiating the roles and permissions of system users.

At the start of the development of SciCrowd, we asked researchers in the field of crowdsourcing to theorize and dwell on the most important aspects and challenges for a hybrid crowd-machine system for scientometric data analysis. The insights obtained from this survey were aligned with the literature on hybrid intelligence (e.g., [17]) to identify metarequirements and refine the design process as originally postulated by Hevner et al. [18]. Therefore, a key challenge that remains to be addressed is the automation of decision-making with explainability features. By putting the algorithm to simultaneously learn from user inputs based on a RLHF approach, we are triggering automated functions to be executed as human-like reasoning processes building up of metaknowledge analysis chains and automated resolution of conflicts [19]. In this form of intelligent data analysis, a cooperation model is responsible for the apportionment of tasks and roles, while a statistics panel must enable users to interactively explore patterns and associations. Building upon the metarequirements derived from the first design cycle, Fig. 1 provides an overview of the overall pipeline of our hybrid intelligent system for supporting quantitative studies of science. This aligns with the interior DSR mode in human-computer interaction (HCI) as described by Adam and colleagues [20]. Specifically, the authors rest their claim for attention upon the construction activities occurring within the design of socio-technical artifacts.

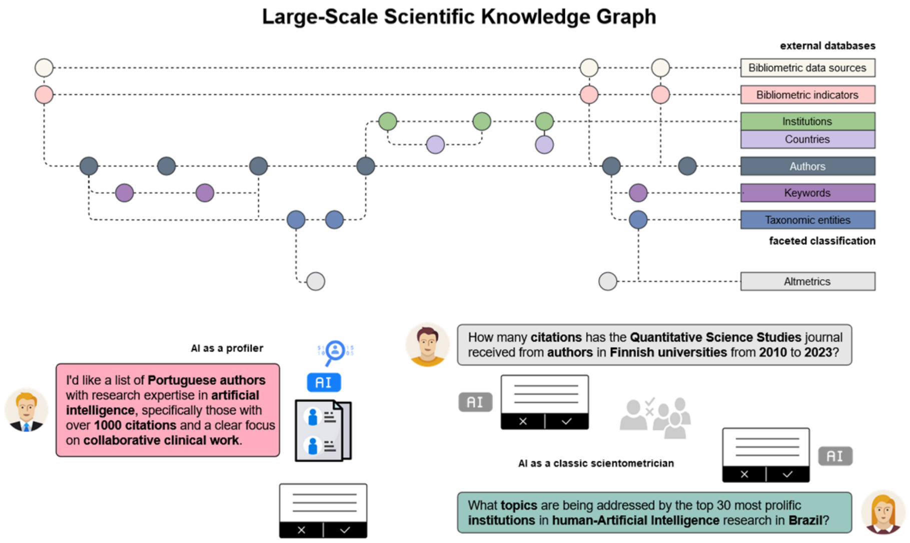

Fig. 1. Overall working diagram of the proposed system.

After the requirements elicitation process, the design principles were then instantiated and translated into the above-described features for further integration into the initial prototype of the SciCrowd system[1]. By incorporating question-based dialogues over linked data in a knowledge graph, AI can act as a mediator of the scientometric analysis process while allowing users to get a depiction of complex phenomena such as topic-institution distribution and inter-institutional collaboration.

3.2 Factors Influencing the Perceived Intention to Use the SciCrowd System based on the UTAUT Model

Throughout the last decades, researchers have used technology acceptance models in multivariate settings to identify end-users' intentions towards adopting socio-technical artifacts. Dwivedi and associates [21] performed a meta-analysis of dependent and independent variables that are constituent parts of theoretical frameworks like the Task-Technology Fit Model and the Technology Acceptance Model (TAM). In this meta-analysis study, the authors focused on the Unified Theory of Acceptance and Use of Technology (UTAUT) as a consolidated version of eight information systems (IS) models. Therefore, a theoretical model of IS acceptance and use prediction was derived comprising the following constructs: performance expectancy, effort expectancy, social influence, facilitating conditions, attitude, and behavioral intention. In general terms, performance expectancy is related to the original TAM construct of perceived usefulness and means the extent to which end-users believe that an IS artifact will help them to achieve performance gains, while the effort expectancy is related to the perceived ease of use of such artifact. When individuals are presented with a new IS artifact, social influence represents the degree to which they assimilate the

[1] https://github.com/trrproject/SciCrowd

others' views on how and in what ways such artifact should be used. Another important construct is the facilitating conditions that can impact the user's intention to adopt a system. These comprise the required resources in accessing information, policies, and behavior physical setting within which the artifact will operate. Finally, the UTAUT model also considers the end-user's attitude as a mediating variable of performance and effort expectancy that exert influence on behavioral intention.

3.2.1 Instrument Development and Qualitative Analysis Procedures

The constructs of the revised UTAUT model presented by Dwivedi and co-authors [21] were used as the basis for the investigation of end-users' individual perceptions and attitudes toward the SciCrowd system. With this in mind, we conducted an online questionnaire survey[2] to collect data as it can be observed in other IS studies (e.g., [22]). In its final version our questionnaire consisted of 19 open- and closed-ended questions and expected to take around 10-15 minutes to complete. Our study draws on the sociological tradition of grounded theory research given the wide and successful use of this method within the field of IS. In particular, we used a qualitative coding procedure described by Corbin and Strauss [23] to identify the underlying factors and potential determinants of the use and adoption of the SciCrowd system. To do this, we employed an inductive strategy to code the qualitative data and uncover the potential facilitators (drivers/enablers) and barriers (inhibitors/blockers) that may influence the behavioral intention to adopt a hybrid crowd-algorithmic scientometric data analysis system. This is aligned with previous studies of the UTAUT model constructs (e.g., [22]). Therefore, we followed a two-step approach where the data were open-coded manually until a stable list of themes emerged through multiple rounds of reading and iterative coding. After breaking down the codes analytically, axial coding was used to compare similarities and differences among the codes. Since the qualitative open-ended survey responses addressed several 1st- and 2nd-order themes related to the UTAUT constructs, the grounded theory approach allowed us to go beyond binary labels of positive or negative intention towards the use of a technology to better appreciate the factors that might affect the adoption of such systems by identifying what is valuable to potential users. The reader is referred to Correia et al. [12] for a detailed insight into the survey instrument design and implementation, along with the influencing factors of crowdsourcing researchers' behavioral intention to adopt a human-AI scientometric data analysis system involving crowdsourced inferential modelling.

3.2.2 Findings of Qualitative Data Analysis

As the creation of analytical and data-driven models is increasingly relevant in today's triple-helix contexts where science and technology evolve, designing a hybrid system remains challenging and can result in erroneous data, unpredictable behaviors, and intrusive actions. With the ever-growing interest in bibliometric-enhanced IR from both academia and industry, we see agreement among respondents on the relevance of comprehensiveness in retrieval coverage for analysis purposes. In particular,

[2] The questionnaire is available at: https://forms.gle/hQaPLMo1PDZWqCU46

some informants stressed the need for accurate retrieval results by means of high precision and recall rates. As an example, one participant mentioned that their interaction with a system of this nature tends to concentrate on more delimited subsets, rather than attempting to encompass the vast entirety of a given scientific field or discipline. This highlights the necessity of a faceted search mechanism to answer questions on any attribute over large corpora. On the other hand, the lack of support for semantic search and the difficulty of finding topics due to the limitations in the search query syntax can be potential inhibitors. Extrapolating to the data-related aspects, the automatic identification of semantic linkages is seen as a key to success, as corroborated in prior studies [13]. From the standpoint of a crowdsourcing researcher participating in the survey, a distinct need emerges for the establishment of more robust connections among diverse elements such as the data itself along with the terms and methods employed for utilizing and analyzing the data. In a broad sense, all of those aspects give insight into the usefulness, use cases, uses, and usability of the data. Respondents advocate that input data must be transformed and translated into a standardized format to be further used in later stages or as input to computational models.

From an inhibition view, reported barriers include the difficulty of avoiding data overload, data incompleteness and noise, proprietary access restrictions, and poor performance in entity matching. As one participant articulated, transparency is key to better understanding why the data are collected and how they are used. Furthermore, provenance holds the potential to enhance data exploration when the system is tailored to support users in consistently tracking knowledge accumulation processes. This affords the possibility of revisiting and reviewing the evolving state of knowledge while enabling seamless navigation between different temporal points, as emphasized by a few of the informants when considering the need for data on large spatial and temporal scales. This agrees with recent studies devoted to novel relevance ranking methods based on citation overlaps [24]. An important issue that arises when designing a data-centric pipeline incorporating hybrid intelligence is the governance required to ensure the quality and integrity of data [17]. Among the aspects identified, we found that visualization features are critical for the accurate analysis of documents describing scientific and technical progress [25], such as graphical representations of citation and co-authorship data.

Another aggregate dimension from the grounded theory analysis is related to the platform itself. From user interface design to interoperability, there is a set of factors that can make a difference in terms of technology acceptance. For instance, gamification elements have been investigated within the context of crowdsourcing systems as a way of engaging users [26]. Regarding the legal and ethical issues underlying human-AI systems, participants raised concerns about the possible lack of fairness and consequent discrimination by the platform, a growing space of inquiry [27]. Also key in the ultimate acceptance of the technology is the ease of use, which relates to the UTAUT construct of effort expectancy. In this vein, an implication for design relies on reducing the effort needed for setup and overcoming the limited configuration capabilities that might be a barrier for widespread adoption. Informants also acknowledge the importance of implementing user-friendly algorithms to improve performance, reflecting the UTAUT construct of performance expectancy. From a scientometric viewpoint, we can automatically perform cross-data inferences and correlations while elaborating explanations of what is discovered.

Multiple factors can support the decision to crowdsource or not [28] and such inherent barriers were identified in our analysis. At the motivational capacity level, incentivizing and sustaining participation are known challenges in most citizen science and crowdsourcing projects and there is a need to "[…] *keep questions and observations simple to get the crowd to engage*", as noted by one informant. In such arrangements, the crowd can be responsible for creating or validating observations of targets of interest for research through the provision of ontologies that allow the selection of classes, descriptions, and metadata. Moreover, the self-assessed confidence in the accuracy of the outputs offers an opportunity to perform data reliability checks; however, it also introduces certain concerns, such as the potential for extreme overfitting and crowd bias. Ample evidence suggests that the attribution of credit for work done, by making sure that humans see their own contributions as part of a whole, may also contribute to the success of crowdsourcing solutions. Looking at the observations provided by the participants, social discussion in the form of feedback (e.g., comments) is essential to engage participants, but may be challenging to scale. In sum, while humans are unable to analyze the full spectrum of scientific activity, AI algorithms often fail to capture the complexities of scientometric data so there is a need for effective approaches to overcome problems like tardiness and poor interpretation of scientific output. Alongside this, some informants pointed to error tolerance and accountability for wrong outcomes as barriers to the meaningful use of AI-infused technologies. To mitigate these issues, we assume that a hybrid crowd-algorithmic solution constitutes a valuable instrument to interpret complex patterns from data attributes and combinations thereof. The notion of complementariness was stressed by one respondent in the following terms: "*A hybrid approach makes sure that the developed solution scales to large amounts of data (thanks to the machine intelligence) and comes closer to solving real-life problems (thanks to the human intelligence).*" This relates to the Elshan et al.'s [29] requirements elicited for a hybrid intelligent system able to foster human-AI partnerships through interactive feedback cycles, explanations, and control mechanisms.

4 Final Remarks

Today's public and private decisions rely on scientometric indicators and science in general as never seen in history. However, we are still only beginning our journey to overcome the limitations of AI algorithms in the uncharted territories of scientometric analysis and the expanding landscape of human-AI interaction, which has brought not only a set of possibilities but also risks and challenges. This paper applied IS theories and methods to understand how hybrid crowd-algorithmic approaches can improve our ability to assess scientific knowledge production and diffusion. In this work we reported on a DSR project for the design and development of a human-centered system pipeline combining automatic indexing and crowd-based processing. The practical implementation of this socio-technical artifact was informed by a series of observations obtained from scientometric studies and through a survey with experienced researchers with diverse backgrounds. We elaborate on these insights to assume that there are inherent challenges to design a RLHF model that learns from crowd behavior while providing a self-adapting system in which the user can validate the outputs provided by the algorithm. As a result, novel design and evaluation principles will be further explored, while usability tests are needed to gain insight on user activities that can better inform the development of a hybrid intelligent system of this nature. In the future we also intend to examine perceptions from researchers in other fields.

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