Thirty years of sense and sensibility in Agent-Based Models: A bibliometric analysis

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Abstract. Emotion and cognition are at the core of human behaviour and modelling human behaviour is at the core of social simulation. Using a bibliometric analysis of publications connecting agent-based modelling with cognition (sense), emotion (sensibility), or both, this study describes the evolution of the field, explores trends, and identifies existing gaps, and proposes potential future developments. Our results indicate that Sense and Sensibility research tracks have seen a significant growth over the last 30 years and a sustained interest with regards to the agent-based modelling community as a whole. However, results also show that such research has issues reaching beyond computer science venues and that, despite its important demands in terms of competence building, relatively few researchers become regular contributors of the field.

Keywords: Agent-Based Models · Bibliometric Analysis · Cognitive Models · Emotion Models

1 Introduction

Modelling human deliberation is at the core of the development of Agent-Based Models (ABMs). ABMs are fundamentally a method dedicated to observe, analyse, and understand the past, present, and future trajectories and dynamics of actual and potential social systems based on simulating individual behaviors, in most cases, human behavior resulting from human deliberation [28]. Most existing ABMs bring about, often implicitly, strong assumptions on the process of human deliberation, such as (economic) rationality (e.g. the mind as a reward-optimization machine [15]), and statistical approaches (e.g. decisions as statistic occurrences [6]). Whereas these models provide reasonable heuristics that can be sufficiently close to reality for particular situations (e.g. marketplace trading) or at the agglomerated level, they become blunt when more advanced models of the mind are required as these heuristics contradict fundamental psychological findings and intuitions [9,11,18,20,26,29,31,34]: human deliberation is subject to and adaptive to a broad palette of internal mechanics that also include aspects such as emotionally-driven actions and reactions.

Despite seeking to understand, (mentally) simulate, and anticipate the dynamics of the intellectual machinery that yields to human behaviour is an innate ability as old as humanity and the object of millennia-long scientific interest

[22], building generative models of deliberation, in particular with computational methods, is not at all straightforward given the complex and adaptive intellectual machinery carrying this deliberation. To this day, the oversight of the field of modelling human deliberation remains limited, mostly grounded in reviews that focuses on contents, thus providing only limited coverage on critical quantitative trends: How many papers? How many authors? Which venues? Is the field growing? If we are to drive the field to greater fruition, we need to have access to such key information. As part of a larger research initiative dedicated to mapping the field with minimal inclusion of specific psychology-related assumptions, this paper engages into a bibliometric analysis of the publications connecting agent-based modelling of human deliberation, with 1) cognition (reason), 2) emotion, or 3) both, in particular developing a cross-analysis of the evolution of these three research tracks along the trends of authorship and productivity over time, towards identifying trends and identifying opportunities for community development. Out of space consideration, this paper is dedicated to analysing scientific productivity metrics and identifying the overall trends of the field as a whole. A complementary analysis of communities and contents (e.g. key background, key concepts, disciplines) is left of future work.

For structuring this analysis, we rely on two-axes classification of psychological components [21,28,20]: cognition ("Sense") and emotion ("Sensibility"), which we believe is commonly relied upon when seeking to develop agents based models of the mind in ABMs. Cognition is usually related to mental processes involving higher functions of the brain, such as decision making, calculation, memory, planning, and problem solving. Emotion is related to how people feel and their intuitive or unconscious decision-making process. In our analysis, we label as the "Sense" research track the publications connecting agent-based modelling only with cognition, as the "Sensibility" research track publications connecting agent-based modelling only with emotion, and as the "Sense & Sensibility" (S&S) research track publications involving both cognition and emotion. For each of the three research tracks (Sense, Sensibility, S&S), the research question of this study is formulated as follows: *What are the general trends regarding research productivity, publication types, authors, and publication venues?*

2 Related Work

To our knowledge, this current study is the first bibliometric analysis of publications that connect ABMs with cognition and/or emotion. However, there are some previous studies that either review how cognition and/or emotion are modelled with ABMs or use the same analysis method for assessing publications on ABMs in general. We include here a brief summary of both types. Our study complements this related work by providing a bird's-eye view over the productivity of the field.

Several studies review the landscape of modelling cognition and/or emotion in ABMs. [5] provide a comprehensive overview of agent decision making architectures and reports how these architectures model cognition and emotions.

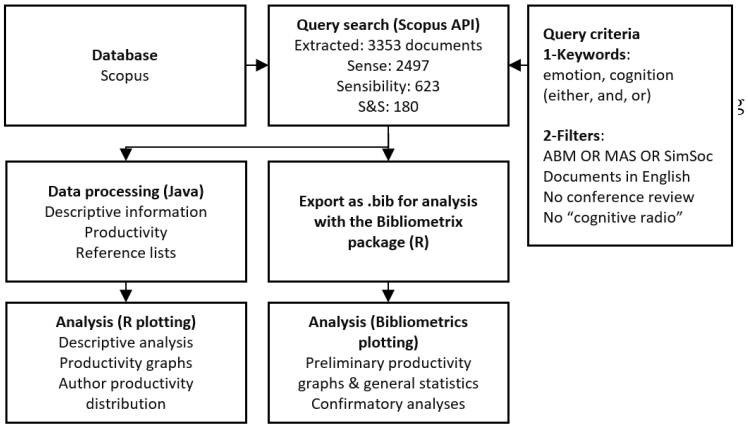

Fig. 1. Flowchart of the data collection and processing steps

All of the 14 such architectures detailed in this study included a cognitive level (ranging from production rule systems to complex cognitive architectures), but only three of them considered emotions. This study is followed by [2], which overviews the possible variants of the Belief-Desire-Intention agent-architecture, including the extensions that incorporate emotions. Analyses of how emotions in general are formalized in ABMs can be found in [1] and [8], with an overview of Normative Emotional Agents in [3]. Looking at specific emotions, [17] have performed a systematic literature review of anxiety in ABMs.

When it comes to the method used by our study, there are several bibliometric analyses of publications involving ABMs that have been published in the last years (e.g. modelling the COVID-19 pandemic [33], ABMs in Operations Research [27], ABMs in finance [32]). However, the topic of modelling cognition and/or emotion has not been surveyed under the lenses of bibliometric analyses.

3 Methods

Bibliometric analyses focus on identifying statistically significant patterns from bibliographic meta-data of a large-scale corpus (>100 documents). The standard bibliometric analysis method involves the following steps: 1) selecting a database; 2) selecting queries; 3) extract document meta-information from this query; 4) filter irrelevant documents; 5) transform the raw bibliometric data in statistically-informative representations (e.g., plots, metrics); 6) analyse these representations and derive insights towards answering the research question(s). Figure 1 summarizes the steps undertaken by this current study.

Database The Scopus database, through the Scopus API, was selected, as it offered: 1) strongly structured data with non-ambiguous unique identifiers for every paper and author; options for advanced database manipulations when combined with programming; a larger amount of publications covered; and was acknowledged to be better suited for multidisciplinary and international analyses (albeit Social Science and Humanities tend to be underrepresented) [13] [30]. As a limitation with regards to alternative databases, such as Web of Science, and non-API Scopus-based extraction methods, further programming steps for collecting and processing the data were required.

Queries The research question intersects 1) agent-based models and 2) any of Sense, Sensibility, and S&S tracks, leading to queries, formally defined as:

SENSE-ABM, SENSIBILITY-ABM, and SAS-ABM, which structured as the intersection between: the considered research track, documents on ABM, the considered timespan, minus excluded papers. Formally:

SENSE-ABM = SENSE AND ABM AND YEARS AND LANGUAGE AND FILTER-IRRELEVANT AND NOT SENSIBILITY,

SENSIBILITY-ABM = SENSIBILITY AND ABM AND YEARS AND LANGUAGE AND FILTER-IRRELEVANT AND NOT SENSE,

SENSE-AND-SENSIBILITY-ABM = SENSE AND SENSIBILITY AND ABM AND YEARS AND LANGUAGE AND FILTER-IRRELEVANT, where:

```
ABM = TITLE-ABS-KEY("social simulation") OR
    TITLE-ABS-KEY OR TITLE-ABS-KEY("agent-based model*") OR
    TITLE-ABS-KEY("individual-based model*")
    OR TITLE-ABS-KEY("agent-based simulation") OR
    TITLE-ABS-KEY("multi-agent system") OR
    TITLE-ABS-KEY("agent-based computing")[3]
SENSE = TITLE-ABS-KEY ("cogni*"); SENSIBILITY = TITLE-ABS-KEY ("emoti*");
YEAR = (PUBYEAR>1989 AND PUBYEAR<2021); LANGUAGE= LANGUAGE("English")
FILTER-IRRELEVANT=NOT DOCTYPE(cr) AND NOT TITLE-ABS-KEY("cognitive radio")
```

Removed papers include: Conference Reviews (which create false-positive duplicates of other papers), papers mentioning "cognitive radio" (a technology for radio communication unrelated to agents). The keywords for SENSE and SENSIBILITY were selected to relate to the topics of "emotion" and "cognition" (i.e., emoti* and cogni* respectively), as these are commonly used for qualifying well-distinguished psychological factors opposing rational, deliberate, calculative and irrational, impulsive, reactive deliberation [23]. Albeit this dichotomy is debated in psychology, to our knowledge, no consensual taxonomy qualifying these facets of deliberation is available and these terms are commonly used in ABMs dedicated to develop advanced models of the human mind. Further terms related to the tracks were considered (e.g., affect*, sad*, rational*), but were left out as they raised false-positives (e.g., rationality or affect(ing) are often evoked in different contexts) or introduces biases about psychology theory (e.g., "joy" assumes a specific theory of emotion).

Data gathering The data was extracted via the Scopus API using an in-house Java program. The raw data was locally saved as text. Key information used in the analysis included: title, venue, author information (i.e., author IDs), affiliations, institution information (country of origin). The number of ABM documents was obtained as the result count of the query ABM AND YEARS AND LANGUAGE AND FILTER-IRRELEVANT.

Document filtering An analysis of the first collected data identified documents that could be filtered directly in the query through the FILTER-IRRELEVANT subquery. No further filtering step was required. In total, 151 papers were removed

[3] Variants were added removing "-" or replace them with spaces (e.g. "agent based model*").

Description	Sense	Sensibility	S&S
Number of documents retained for analysis	2497	623	180
Number of books	20	0	1
Number of book chapters & editorials	153	24	13
Number of conference papers	1518	456	119
Number of journals	806	143	47
Number of raw publication venues	1191	308	113
Number of different authors	5253	1454	405
Number of author appearances	7443	2039	544
Number of documents per author	0.48	0.43	0.44
Number of appearances per author	1.42	1.40	1.34
Number of co-author per document	2.98	3.27	3.02

Table 1. Overview of the dataset

because of mentioning "cognitive radio" and 277 documents were removed because of being conference reviews.

Data processing The data was gathered using an in-house Java-based library and then following two processing pipelines. First, the collected data was turned into a bibtex file that followed the same structure when generated by the Scopus website, except with more structured references and then processed into plots using the Bibliometrix package [4], an off-the-shelf, broadly used bibliometric statistical analysis tool. Second, processing steps were directly performed within the Java library and exported in a R-compatible format for metrics and plots that were not provided by the Bibliometrix library. Implemented representations included: general bibliometric information, absolute and field-specific productivity curves, country distributions (as in [19,24,25]). As to strengthen the validity of data transformations and pipelines, redundant analyses were carried by both pipelines and demonstrated identical results.

4 Results and Discussion

4.1 Overview of Bibliometric Data

Table 1 provides an overview of the general metrics tied to the dataset and Table 2 lists of the venues that have received the most publications, which conveys key information about the three research tracks. As statements covering all three research tracks, the proportion of **documents per publication venue** shows a proportionally large number of venues (in average about two documents per publication venue) and thus a scatter of documents along numerous venues. Table 2 allows obtaining insights on the nature and distribution of these venues, showing in particular an overwhelming skew over two venues: Lecture Notes in Computer Science (LNCS), which is a collection of conference proceedings, and the International Conference on Autonomous Agents and Multiagent Systems (AAMAS), which, on their own agglomerate more publications than the following 28 entries summed up. This result appears to be confirmed by the significant

preference for conference over journal papers and book chapters[4], visible in in Table 1, which is a common practice in computer-science research.

As a cross-comparison, based on the data in Table 1 shows a significantly stronger interest towards Sense over Sensibility (about 4× more) and a similar scale between Sensibility and S&S. Adding the categories, about 7% of the papers evoking cognition also evoke emotions and about 22% of the papers evoking emotions also evoke cognition. This imbalance shows that papers evoking emotions are more likely to evoke cognition than the other way around. It may be hypothesized, but further evidence is required, that papers evoking emotions are further grounded in a psychology discourse than papers evoking cognition.

The relative proportion between the number of conference papers, journals, and book chapters brings forward that a greater proportion of Sensibility papers is submitted in conference venues (73%) over Sense (60%) and S&S (66%), which may suggest a greater establishment of the Sense community as well as different distributions over the communities. These observation seems to be confirmed by the publication venues in Table 2, which shows journals specialized to the Sense track topics and publications (e.g. Cognitive Systems Research, Cognition and Multi-Agent Interaction), whereas no such a venue is visible for the Sensibility track: venues in which Sensibility track is similarly or more represented than Sense track are all generalist CS venues (e.g. Communication in Computer and Information Science, ACM International Conference Series) in which Sense documents are published as well. In other words, there seem to be established specialized/exclusive arenas for Sense research (albeit with limited outreach as each of these venues cover less than 1% of all Sense publication); whereas none for Sensibility and S&S research tracks, which are published in generalist tracks. The number of publications per authors is relatively higher for both Sense & Sensibility than the other two topics independently, and the number of co-authors per document appears to be higher for Sensibility papers, albeit the difference is too small for drawing strong conclusions.

Overall, this overview allows to bring into light a few overarching deductions: 1) the Sense track has received significantly more contributions than the Sensibility and S&S tracks; 2) all three research tracks appear to be overall **relatively scattered** across a wide range of publication venues, suggesting a **re-occurring interest across communities** for these three tracks; 3) Sense research offers **(limited) specialized arenas** and Sensibility and S&S research show no specialized venues; 4) Sense or Sensibility research is **predominantly published in computer science** venues, in particular in LNCS and AAMAS; 5) for all three tracks, there is a **high author turnover**; 6) all three tracks appear to be **similar** in their metrics: number of authors per paper, number of paper per author, publication venues.

Sense	Sensibility	S&S	Venue
374	96	37	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)
169	88	25	International Joint Conference on Autonomous Agents and Multiagent Systems
34	18	4	Advances in Intelligent Systems and Computing
29	15	3	CEUR Workshop Proceedings
32	6	2	Journal of Artificial Societies and Social Simulation
17	16	1	Communications in Computer and Information Science
11	14	2	ACM International Conference Series
11	10	2	Smart Innovation, Systems and Technologies
11	6	2	PLoS ONE
18	0	0	PIE - The International Society for Optical Engineering
14	1	2	Procedia Computer Science
14	2	1	Frontiers in Artificial Intelligence and Applications
14	2	1	Computational and Mathematical Organization Theory
16	0	0	Cognitive Systems Research
13	3	0	AAAI Fall Symposium - Technical Report
9	6	0	Physica A: Statistical Mechanics and its Applications
14	1	0	IEEE International Conference on Systems, Man and Cybernetics
11	2	1	Studies in Computational Intelligence
13	0	1	Springer Proceedings in Complexity
8	4	2	IEEE/WIC/ACM International Conference on Intelligent Agent Technology, IAT
6	6	1	AAAI Spring Symposium - Technical Report
12	0	0	Winter Simulation Conference
7	4	1	Expert Systems with Applications
5	5	1	IFIP Advances in Information and Communication Technology
10	0	1	Cognition and Multi-Agent Interaction: From Cognitive Modeling to Social Simulation
7	1	3	Advances in Intelligent and Soft Computing
11	0	0	AAAI Workshop - Technical Report
7	2	1	Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics
7	1	1	Simulation Series

Table 2. Publication venues with the most number of publications, sorted by number of publications summed across all tracks. The color indicates the disciplinary origin of the venues: computer science and engineering in blue, hybrid social science and computer science and social simulation in yellow, generalist in black, cognitive science in green, and interdisciplinary science in purple.

4.2 Author distribution

Authorship metrics reported by Figure 2 suggest an average of three co-authors per document, which is similar to average values in computer science [14] shows further evidence of the prevalence of computer science practices in all three topics. Moreover, for all three tracks, Figure 2 shows seemingly low number of documents per author and low number of appearances per author for all three tracks. This unexpected discovery, lead us to further investigate the distribution of authors with regards to the number of documents shown in Figure 2, which shows that about 80% of the authors contributed to only one paper and more than 90% of all authors did not contribute to more than two papers, indicating a **high turnover** in the community. On the other side of the tail, about 50 authors were each included in 10 documents or more, indicating the presence of a *solid core of competence*, yet diluted when considering the considered 30-years timespan.

[4] This ratio is likely to be greater in reality, as Scopus is known to underrepresent conference proceedings in comparison with journal papers [30]

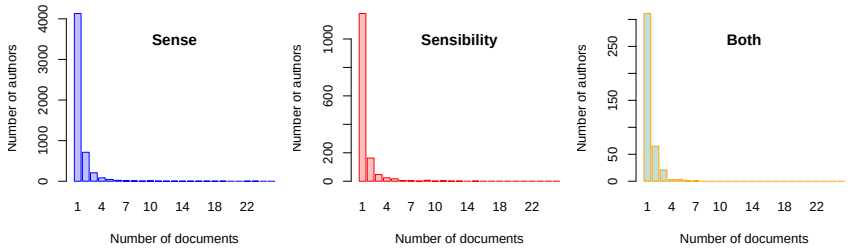

Fig. 2. Distribution of the number of documents per author

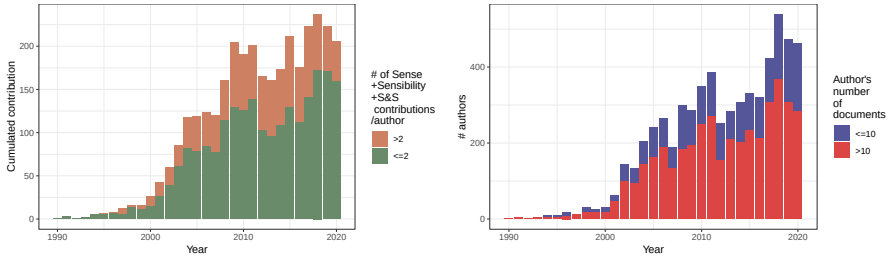

Fig. 3. On the left, evolution over time of the cumulated contribution over all three tracks added of occasional Sense, Sensibility or S&S contributors (in green, with two papers or less) and regular contributors (in orange, with more than two papers). On the right, evolution over time of the number of short-career (in purple, 10 publications or less) vs. long-career (in red, >10 publications) of occasional contributors who contributed their first Sense, Sensibility or S&S paper in a given year.

Facing this surprising result, further investigation was undertaken. It is possible that the sharp increase in the number of PhD candidates in the last two decades, and who are more likely to have shorter research careers [16], can explain this outcome. Figure 3 offers some insights on this question by measuring the overall contribution of *occasional contributors* (i.e. contributors with one or two papers in all Sense, Sensibility, and S&S tracks added) relative to *regular contributors* over time, where this contributions is measured through summing of all O_d/A_d for all documents d published in a year, where O_d is the number of occasional contributors and A_d is the number of authors in the document d. Figure 3 also shows the evolution of the lengths of the overall career tracks of the occasional contributors, where a career track is considered as long when it has more than 10 documents and short otherwise. Due to the boundaries of data-collection, the last years may be skewed and are disregarded for analysis.

The results indicate that, overall, the absolute contribution of occasional as well as regular contributors has significantly grown over time, while preserving similar proportions to each other (occasional contributors sum up more than twice more contribution than regular contributors). The number of short-career occasional contributors has markedly grown over time. However, very surprisingly, the number of long-career occasional contributors is significantly higher than expected and than the number of short-career occasional contributors, with a stable proportion of slightly more than twice the number of long-career researchers over the number of short-career researchers.

Summing up, these findings are particularly critical in the light of the extensive competence required for developing Sense, Sensibility and S&S ABMs. The high turnover indicates that, at the individual level, an extensive amount of effort is invested but not capitalized upon, while at the community level, there may be limitations for expertise, research, and methodological sustainable build up over time, albeit a core of expertise that has, in absolute, grown over time. As a potential explanation for the prevalence of long-career occasional researcher derived from the requirement for producing Sense/Sensibility/S&S research, the contributions may be the fruit of collaborations between, on the one hand, regular Sense/Sensibility/S&S researchers who bring the modelling competence, and on the other hand, established researchers from other disciplines who bring domain competence for one specific simulation without further adopting the methodologies. While further investigation is required for confirming this finding (e.g. through network and disciplinary analyses), a key question remains open: can these experienced researchers be retained?

4.3 Research Productivity

Figure 4 indicates the quantity of documents per year, as well as the frequency of these documents regarding the general field of ABMs (formally represented as the number of documents of the research track divided by the number of ABM publications on that year). This proportion allows assessing whether the field is growing in importance relative to the agent-based modelling field, as the number of ABM publications has significantly changed over time.

Results indicate for all of three tracks a significant growth between 2000 and 2005, followed by a plateau of productivity since then, with ups and downs deviating from a time-windowed average by roughly 20% from one year to the next. This growth, when crossed with the frequency of the research tracks with regards to the ABM field (the red line), which remain is relatively over time, indicates that this significant growth follows a proportionally similar significant growth in the ABM field overall, i.e. the interest has been spiking to the same degree with the interest in ABMs in general. The frequency with regards to the ABM field in general is relatively stable over time for all tracks, with a slightly downward trend for Sense and a slightly upward trend for Sensibility. Overall, these patterns suggest that the interest for the three tracks is a side-product of an interest for ABM in general more than a trends growing on their own.

5 Limitations

Bibliometric analyses have some limitations, which we list here. They is bound by the data they rely on, which offers only a limited observability and precision in regards to the contents of the research (e.g., conceptual frameworks), the communities, and social factors. Building over statistical methods, bibliometric analyses are sensitive to the limits of these statistical tools and thus require cautious interpretations in regards to the accumulated evidence. As an approach, the

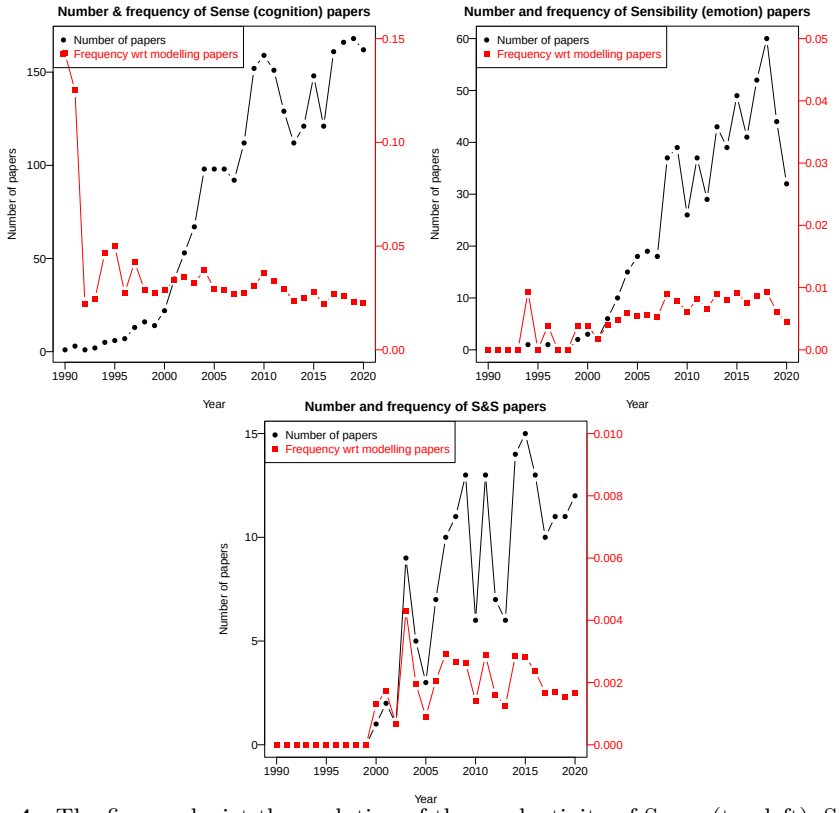

Fig. 4. The figures depict the evolution of the productivity of Sense (top left), Sensibility (top right), and S&S research tracks over time. The black lines depict to the raw number of papers per year and the red lines depict the frequency relative to the field of ABM in general. Note that the scale vary per figure.

results developed by this article are grounded in converging statistical evidence, coupled with confirmatory statistical analyses and by-hand verification, both at random and when encountering surprising findings. Moreover, the analysis depends on the Scopus database and queries, which may introduce biases [13,30], false-positives and false-negatives. For covering these issues, we relied on a single, non-ambiguous keyword per query. As to reduce country-sensitive bias and false positive due to language, the research was limited to documents written in English. As a side effect, non-English-speaking countries may be underrepresented with regards to English-speaking countries. The provided numeric results are likely under-estimates, albeit the distributions can be expected to approximate the reality relatively faithful.

6 Conclusion

Using a bibliometric approach, this study analyses the meta-data of ABM-related 3300 documents (retrieved by Scopus) and connected to the topics of only Sense (cognition), only Sensibility (emotion), and both Sense & Sensibility (S&S).

As a key takeaway, the topic of making ABMs of the mind has demonstrated an **enduring interest over time** during the last 30 years, with 6707 authors in 1408 publication venues and a cruise speed of 150 new papers per year for Sense, 50 papers for Sensibility, and 10 papers for the S&S track. The absolute interest has been growing, from an early phase from 1990 to 2000, a rising phase, from 2000 to 2010, and a stable, high-productivity phase since 2020.

Despite this success, the analysis brought into light some significant concerns. While the interest for modelling the mind is sustained, the community seems to face a marked turnover, with around 80% of the authors appearing only once and more than 90% appearing no more than twice, which is critical for such interdisciplinary research tracks that are highly sensitive to long-term personal competence and network building. Moreover, this interest appears to be overwhelmingly expressed in the field of computer science, with limited scientific outreach into social sciences venues, despite the fact that such venues were the intended users of ABM as a method [7,10,12]. As a possible interpretation, motivated by the observation that Sense, Sensibility, and S&S appear to be a constant fraction of ABM-publications over time, is that most of the Sense, Sensibility, and S&S-related research is a side-product of ABM-related research more than a (self-)recognized field on its own –as if a large fraction of modellers and non-modellers invited for a collaboration happen to face a Sense and/or Sensibility-related case once in their career, solve it, and publish once about it before moving on to other interests. The conducted analysis showed some evidence in this direction, but further investigation is required for obtaining a more complete overview, such as an analysis of the networks, of the contents, of the involved disciplines. Despite this overall tendency, the results also show a core of stable researchers: the 30 years period has seen around 50 authors with ten or more publications.

As closing remarks, these findings also indicate exciting opportunities for the future. This analysis reports that embedding models of the mind in simulations has been, is, and likely will be a recurrent source of interest for the ABM community. As research we all undertake now as a collective lays the groundwork for future researchers, it becomes of the highest importance to establish ourselves as a *human capacity-oriented community* that can create the right conditions for its participants, often experienced researchers who dared to venture into the interdisciplinary realm of Sense and Sensibility and invested in the required learning, to sustain their interest over time and to reach out towards the disciplines that have the potential to benefit from it the most.

Acknowledgements

The authors wish to thank the reviewers for their constructive suggestions. This research has been conducted within the frame of the Anxiety-Sensitive AI initiative (AnxSAI)[5]. This research has received the technical support of Elsevier,

[5] `https://www.umu.se/en/research/projects/anxsai-anxiety-sensitive-artificial-intelligence/`

which gave access to the "cite-by" function within the Scopus API. The first author acknowledges the financial support of the Knut and Alice Wallenberg Foundation (project number 570080103) and Umeå University. The second author acknowledges the financial support of the project "FUTURES4Fish: Adaptive socio-technological solutions for Norwegian fisheries and aquaculture", funded by the Research Council of Norway (project number 325814).

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