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AGENT-BASED MODELS: IMPACT AND INTERDISCIPLINARY INFLUENCES IN ECONOMICS

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Agent-Based Models: impact and interdisciplinary influences in economics

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Abstract

Abstract: In the present paper, we investigate the diffusion of agent-based models (ABMs) in economics using a quantitative approach to better understand how the introduction of this tool in economics influenced the structure of the field as well as research programs in recent years. Our analysis shows that the proliferation of ABMs has resulted in the emergence of diverse research subfields rather than one unified research program. Most notably, we highlight how interdisciplinarity plays a pivotal role in understanding the diversity of ways in which agent-based models are integrated into economics. While in some cases ABMs are used by economists as an imported tool to address disciplinary-oriented questions in dedicated subfields journals, in other cases ABMs are a vehicle for more interdisciplinary transfers and interactions (e.g., interdisciplinary co-authorship) that are more challenging to the traditional frontiers of economics.

Keywords: Agent-Based; Interdisciplinarity; Social Network Analysis
JEL Codes: B2; B21; B4; D9

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1 Introduction

While economics is usually considered one of the most insular disciplines (Hausman, 1992; Fourcade et al., 2015), it did not escape the wave of interdisciplinary which globally impacted all the social sciences in the early 1990s (Angrist et al., 2020; Truc, 2022b). If the potential "interdisciplinarity turn" in economics is still recognized as being of a lesser magnitude than in other social sciences (Truc, 2022b), one can nevertheless identify at the "local" level the emergence of a few research programs which developed at the frontier of economics (Davis, 2019).

The formation of these research programs often relies on the importation of tools and methods from other disciplines, a phenomenon generally seen as a source of innovation in science (Nissani, 1997; Humphreys, 2004; Andersen, 2013). One notable successful example has been the importation of experiments from psychology by behavioral and experimental economists to develop their own hybrid methods and research programs. More recently, another fertile ground for the dissemination of knowledge across economics disciplinary lines has been the importation of computational methods and complexity approaches in economics.

Great attention has been paid to what computational methods can do for economists (Colander, 2015, p. 264; Backhouse and Cherrier, 2017), how it transformed the relationship between theoretical and applied work (Backhouse and Cherrier, 2017) or its potential relevance for economics or contemporary historical and philosophical questions (Colander, 2014; David et al., 2020). Despite important efforts to clarify the conceptual definitions of computational or complexity economics, the field remains largely elusive historically and empirically. Similarly, the interdisciplinary nature of computational methods is often taken for granted as these tools are considered to stem from outside of economics (Davis, 2006, 2008) despite very few historical investigations of interdisciplinary practices and their prevalence in economics.

One possible reason for the lack of such empirical clarifications about "complexity economics" might stem from the fact that the terms encompass a large variety of approaches that have little in common. The diversity and potential heterogeneity within complexity economics led some to favor the term "complexity era in economics" (Holt et al., 2011) because complexity in economics is "an umbrella term or research agenda, rather than a coherent body of thought" (Scrieciu et al., 2021, p.697). Rather than study computational economics as a field or specialty in economics, we instead want to focus on the particular tools and approaches that are used within computational and complexity approaches. For the present article, we focus on one increasingly successful tool in economics with agent-based models (ABMs).

There are at least two dimensions to the emergence agent-based models in economics in relation to the frontiers of economics. The first dimension is that the importation of new tools, methods, or models from computational sciences is in itself interdisciplinarity. Simulations or agent-based models are not part of the standard toolkit of economists despite the fact that these methods have existed for multiple decades in other disciplines. One can expect that if economists were to increase the use of ABMs, the landscape of economics could be radically altered. A second dimension is that computational methods like ABMS,

or "computational template" (Humphreys, 2004), are themselves a vector for interdisciplinarity. Computational templates are "genuinely cross-disciplinary" because "they draw together computational methods across scientific domains, domains that often have very little in common" (Price, 2020, p.44). The use of ABMs in economics supposedly makes the importation from other disciplines easier because a computational template can be the same across disciplines. Agent-based models in the natural sciences like physics or ecology, and in social sciences like sociology (Macy and Willer, 2002) or political sciences (Cederman, 2003) reduce the cognitive and methodological gaps that exist between disciplines, thus making interdisciplinarity easier. However, the extent to which this gap narrows in practice requires further investigation.

One particular challenge with ABMs in economics is that the nature of the field is relatively unclear. Agent-based economics can be considered both a research field (a community of researchers) and a tool (a method not bound to a theme or particular epistemological framework). This issue has been noticed in the case of experimental economics too for example. Chris Starmer talks about the tension between "experimental economics as a tool, which you apply in different areas", and experimental economics as a "specialized pursuit, which might make it ghettoized" (Maas and Svorenčík, 2016, p.58).

In the case of ABMS developed in social sciences, all researchers share a common expertise, to some extent, as-if they were part of the same "research program". For example, Anzola (2019, p.1) identifies some methodological homogeneity in ABMs, a common "practical orientation", and high interest in interdisciplinary approaches. Similarly, during the early years of ABMs in economics, members of the Santa Fe shared a common critical perspective of mainstream economics (Fontana, 2010; Fontana and Corsatea, 2013). However, such a general analysis of ABMs in social sciences or in economics as a research program downplays potential internal tensions resulting from the fact that ABMs are also tools that have been transferred from other disciplines and applied by different research groups. Indeed, knowledge transfer can result in different scientific cultures as it is partly shaped by the epistemic context in which it happens (O'Rand, 1992; Morgan, 2014). This was for example the case of the game-theory whose transfers in sociology (Camilotto, 2021) or in different national contexts such as France (Nessah et al., 2021) led to different interpretations and interdisciplinary modalities.

The goal of the present articles is to disentangle these different aspects. On the one hand, there is a dual interdisciplinary role of ABMs in economics: being themselves imported from other fields they are then with no doubt part of the interdisciplinarity process, but one cannot ignore that once introduced in economics, they might become in turn the vehicles for concepts or models imported from other disciplines. On the other hand, the transfer of ABMs in economics might happen in a variety of epistemic contexts which structure the modality of interdisciplinarity.

For the present article, we are interested in how the importation of agent-based models as a method led to the formation (or not) of particular communities in economics with potentially heterogeneous perspectives on ABMs in economics.

2 Methodology

2.1 Corpus

If the Santa Fe is an identifiable anchoring point, since the 2000s agent-based models have spread to a variety of communities that have no connections to this historical origin. Moreover, we find no particular JEL codes or journals that would capture the essence of agent-based economics. Therefore, agent-based economics cannot be simply reduced to a set of journals, authors, codes, or institutions, nor it is possible to easily identify a "core" to the field without risking *a priori* biases.

To achieve our goal we combined multiple sources to find a relevant corpus that covers agent-based papers that are oriented towards economics. To identify such a corpus we used three main strategies (1) Unrestricted keyword search to identify agent-based economics articles published outside of economics, (2) disciplinary-restricted keyword search to identify all agent-based approaches published in economics, and (3) similarity-based topics to identify potential remaining agent-based economics articles that are not capture by keywords or not published in an explicitly identified economics journal:

- 1. Unrestricted keyword search: first, we wanted to identify all relevant articles. We simply search in Web of Science for all papers mentioning "agent-based economics" or "agent based economics" or "agent based computational economics" or "agent-based computational economics" in the abstract, title, keywords by authors, or keyword plus. Keyword plus is a Web of Science feature that assigns keywords to articles based on the title of their references. For example, while an article might not explicitly talk about "agent based economics" in its abstract/title/keywords, it might be identified as relevant if some of its references often contain the searched keywords.

  Simply searching for "agent-based" in all papers would capture a lot of irrelevant papers that are not about economics. We also restricted the search for specific occurrences of the terms search rather than "agent-based" and "economics" to avoid many irrelevant papers that often contain a list of disciplines such as: "agent-based has been applied to sociology, economics..."

- 2. Disciplinary-restricted keyword search: second, we made a disciplinary-restricted keyword search in Web of Science for "agent based" and "agent-based" in abstract, title, keywords by authors, or keyword plus in all articles published in an economics journals. Because these words are unique to agent-based approaches in economics (unlike "heterogeneous agents", or "agent" alone) this should capture only relevant articles.

  To identify "economics articles" and restrict our search, we use two main sources. First, we identify a set of journals using the US National Science Foundation (NSF) classification which assigns one discipline to journals. While having one discipline per journal is particularly useful for this keyword search as we want to restrict ourselves to economics in a stricter sense, the NSF classification might be imperfect. To make

sure we didn't miss anything important, we complemented the NSF list of economics journals by searching for the same keyword on SCOPUS's list of economics journals which is instead tagged-based. Journals can be identified as belonging to multiple disciplines. We looked for particular discrepancies with the WoS-NSF search, and with the exception of the *Computational Economics* journals identified as computational science in the NSF classification, we found a similar list of articles published in the same journals. To correct for the *Computational Economics* discrepancy, we simply added this journal to the list of the NSF in our WoS keyword search.

- 3. Similarity-based topics: third, we identify a list of relevant articles by using the Microsoft Academics database. One particularity of the database is that articles are classified according to hierarchized and non-mutually exclusive fields of study and topics. These classifications are created using artificial intelligence and based on similarity measures which include contents of items, authors, and other variables to identify the discipline and topics of individual items. Whether we talk about disciplinary classifications (eg., economics) or sub-field classifications (e.g., behavioral economics), the topics are assigned to articles rather than journals. An article can be classified as "economics" even if published in non-economics journals according to the National Science Foundation, Web of Science, or Scopus.

  We found two groups of relevant topics for our search. The first is the combined tags of "economics" and "agent based model" which identify all economics articles using agent-based models. The second is simply the topic "agent based computational economics" which identifies "agent based computational economics" as a specific subfield. From that list, we match the articles identified using their titles and DOI on the WoS database.

From this set of articles, we are able to study a variety of variables ranging from disciplines cited to the affiliation of authors.

To identify the discipline of the journal in which each article in the final corpus was published, we used the US National Science Foundation (NSF) classification system. This system includes 143 fields of research (e.g., sociology, psychiatry), which are themselves grouped under two large domains: natural sciences, engineering, and biomedical sciences (NSE) and social sciences and humanities (SSH). For our own classification, we first grouped nine sub-categories of psychology into one category, and we focused our attention on the most highly represented disciplines within the final corpus: .

We also study author affiliation. Studying affiliation raises multiple questions. How to handle authors with multiple affiliations or how to compare countries with vastly different organizations? For example, France has one central research institution with the *Centre National de la Recherche Scientifique* that almost always ends up as the most occurring one because many researchers are associated with it one way or another. On the opposite, in Germany, the Max Planck Institutes is split into multiple institutes, which makes the Max Planck either rare (when institutes are counted as unique institutions) or the top institutions (when institutes are grouped).

In our case, we face an additional challenge. Author affiliation was determined using information about authors in the Web of Science database. However, affiliations are not per author, but instead per institutional departments. For example, in the case of an article with two authors from the same department, the department (and institution or country associated with it) is only counted once. Similarly, a single-authored article where the author has three affiliations can result in one article having three affiliations. While in some cases we can infer the institutional affiliation for each author (e.g., one institution, multiple authors), in others we can't (e.g., two institutions, three authors).

For the purpose of this article, we are mainly interested in the relationship between European and American research groups. Namely, how much collaboration we observe between the two groups, and what are their relative importance over time. Therefore, to mitigate some of the biases induced by the ways the database is structured, we restructure the information in two ways. First, for each article, we only kept one occurrence of each unique institution (university, research institute...) to avoid the multiplication of observations resulting from the variety of departments observed in some institutions. In other words, for each article, authors are grouped by their institutional affiliation as a research team. For example, in an article with two authors from Princeton and one author from Stanford, we only know that the article was written by one team from Princeton and one from Stanford, but not that the individual ratio was two-thirds. Second, and more importantly, for the purpose of our analysis, we mostly looked at the share of papers authored by European and American economists.

2.2 Analysis

From our corpus, we built bibliographic coupling networks spanning 10 years for each year, from 1999 to the 2018.[1] We built bibliographic coupling networks using the references of our corpus. In a bibliographic coupling network, a link is created between two articles when they have one or more references in common. The more references that two articles have in common, the stronger the link. Bibliographic coupling allows us to measure how similar two articles are in a corpus.

Usually, the relationship between two articles is weighted by the number of references in common, by whether these references are rare or common across the whole network, and by whether the articles citing these references have long or short bibliography (Shen et al., 2019). For this article, we used a different approach with backbone extraction using the Stochastic Degree Sequence Model (Domagalski et al., 2021). The backbone of a network seeks to preserve the network's underlying structure by filtering out less important or noisy edges.

We then plotted the networks or our dataset with 10-year overlapping windows. In the final visualization of the networks, we color-coded the nodes according to clusters detected

[1]The networks were created in R. See the biblionetwork package and networkflow package for more detailed instructions to reproduce results from the present paper (Goutsmedt et al., 2021). Most data treatment and analysis were done in R or SQL.

using Leiden modularity-based algorithm (Traag et al., 2019), and we positioned each individual node using Force Atlas 2, a force-based layout that reduces crossing links (edges) as much as possible. If between two periods two communities share a high number of articles, they are considered to be the same community and keep the same name. More precisely, if more than 55% of the articles in a community at the period t represent more than 55% of a community at the period t+1, then the name is kept between the two periods.

3 An interdisciplinary origins of agent-based models: 1988-2004

One of the main starting institutional points for the history of agent-based models in economics is the Santa Fe Institute. In the early 1980s, members of the Santa Fe were concerned with creating an environment that would help the development of interdisciplinary and transdisciplinary interactions between the social and natural sciences (Gell-Mann, 1988, p.5). Some obvious candidates for these rapprochements were psychology and neurosciences, as well as anthropology and evolutionary sciences. The more general attitude was that a global approach to human behavior, its history, and its evolution, was necessary and that neither cultural nor biological approaches alone could solve these big questions (Gell-Mann, 1988, p.6). These attempts to bridge the social and natural sciences quickly spread to other disciplines like economics whose already existing mathematical inclinations made the discipline a perfect candidate for members of the Santa Fe.

In 1987, a workshop co-chaired by Arrow brought together economists and physicists from the observation that neoclassical theory had shortcomings and that collaboration with researchers from the natural sciences could help new developments in economics (Fontana, 2010, p.169). For most of the economists present, these developments were seen as a way to complement the neoclassical approach, not necessarily as an alternative paradigm. The interactions between physicists and economists were not always easy, and the exchanges led to explicit some of the differences in cultures of both disciplines, including physicists having trouble accepting the simplifications in economics models (Fontana, 2010, p.171). However, it nonetheless proved successful as in 1988 a dedicated Economic program was created within the Santa Fe.

Between 1988 and 1996, the program followed a "strongly heterodox" and "highly innovative" orientation according to Fontana (2010); Fontana and Corsatea (2013). The directorate of the program was first entrusted to Brian Arthur, the "only non-mainstream" economist of the 1987 workshop (Fontana, 2010, p.169). The program included research on agent-based methodology such as the foundational work of Arthur et al. (1997a) on stock markets that would later be applied to other areas. The criticisms of mainstream economics were very explicit during that time, and many developments in the program were seen as providing an alternative approach to the "the traditional topological methods of neoclassical economics" with computational approaches (SFI Bulletin 1990,5,2,15 in Fontana, 2010).

In 1995, Lawrence Blume and Steven Durlauf became the new co-directors, and accord-

ing to Fontana (2010, p.184), this marked a sharp return "back to the mainstream" and a "synthesis period" between 1996 and 2004 (Fontana and Corsatea, 2013). What is most characteristic of this turn is not the fact that the program itself changed, but rather that it enlarged to include a more diverse set of approaches. This includes economists such as Samuel Bowles with access to mainstream positions and journals despite relatively exotic methodology that would become the next director. During the early 2000s, under the directorate of Bowles, the program became a Behavioral Sciences Program and went a different direction and the complexity approach orientation of the program was mitigated.

Between 1989 and 2004, the Santa Fe economic program led to the production of 198 working papers. Among the working papers that ended up published, around 63.5% of them were published in an economics journal, while the others were published in a variety of disciplines with equal importance such as physics, sociology, biology, or mathematics (Fontana and Corsatea, 2013, p.82). While the diversity of discipline in these publications emphasized the interdisciplinary nature of the program, the fact that the majority of these articles were published in economics is a first clue that complexity approaches found room to exist in economics despite resistance.

The history of complexity economics as a Santa Fe program might downplay heterogeneity in the program. The "return to mainstream" identified by (Fontana, 2010), or the acceptance of articles in economics journals might not be true for all areas of "complexity economics". For example, the econophysics approach that developed, "directly in line with development of so-called 'complexity science"' (Gingras and Schinckus, 2012, p.113) had its articles mostly published in physics journals despite the attempt of its members to publish in mainstream journals (Gingras and Schinckus, 2012, p.115).

Moreover, while the history of the Santa Fe is relatively well covered by the literature, what happens in other research centers and after the early 2000s when the program ended remains elusive. As expressed by Fontana (2010); Fontana and Corsatea (2013), the last years of the program were marked by an enlargement of the complexity approach. While the early years were characterized by a handful of actors with similar goals in mind, the complexity program became a lot more diverse in the latter years, including in terms of methods. After the end of the program, the nature of "complexity economics" became even more difficult to grasp as the program had lost its historical institutional anchor. By studying ABMs publications through scientometrics means, we aim to capture how ABMs spread after the Santa Fe, but also how some research directions might have emerged from different origins.

4 Overview of ABMs in Economics

4.1 Agent-Based Models: between the mainstream and the frontier of economics

We collected around 937 articles about agent-based models in economics between 1999 and 2019. The field grew rapidly from around 10 articles a year before 2005, to 50 in 2010, and to 100 in 2017 and 2018. This rapidly increasing number of articles signals an important

shift for the field in the mid-2000s. Most of the articles in our corpus are published in a handful of journals that we can classify into three big groups.

The first group is the journals which are economics-oriented journals but methodologically-specialized in interdisciplinarity approaches and complexity-related fields. Four out of five of the most important venues of publications for ABMS can be identified as belonging to this group (Table 1). Among them, we find the *Journal Of Economic Dynamics & Control* and *Computational Economics* specialized in general computational methods. The *Journal Of Economic Interaction And Coordination* and *Journal Of Evolutionary Economics* are a bit more focused on agent-based approaches and evolutionary approaches respectively. Finally, we find the *Journal Of Economic Behavior & Organization* (JEBO) as the fourth most important venue of publications. The JEBO is more generalist and more prestigious than the other, with an explicit identity as an "eclectic" journal methodologically, with contributions ranging from computational simulation to laboratory experiments.

All these journals have in common to explicitly value interdisciplinarity in their editorial statement. While they are not exactly traditional heterodox journals (such as the *Cambridge Journal of Economics*), they are not exactly mainstream either, and very much at the frontiers of economics as a discipline. This confirms the ambiguous status of ABMs and complexity economics on the orthodox/heterodox spectrum. In the literature, these approaches, along with behavioral and experimental economics, have often been identified as a new type of research program that is part of a potential mainstream pluralism turn (Colander et al., 2004; Davis, 2006, 2008). However, we can hardly speak about mainstream success in the case of ABMs.

For example, the JEBO has been an important journal in the history of ABMs and behavioral economics (Thaler, 1980; Güth et al., 1982; Truc, 2022a). However, the most influential articles in behavioral economics, especially in the early years, have been published in the top five journals such as *Econometrica* (Kahneman and Tversky, 1979) the *Quarterly Journal of Economics* (Laibson, 1997; Fehr and Schmidt, 1999) or the *American Economic Review* (Rabin, 1993; O'Donoghue and Rabin, 1999). In contrast, we find that ABMs in economics are almost never published in the top five. This is not because of a disinterest for top journals by ABMs economists. Among the ten most cited journals in our corpus, we find four of the top five (Table 2). Contrary to what we observe in the history of behavioral economics, we find a relatively asymmetrical relationship between mainstream economics and ABMs approaches. ABMs economists cite top journals but rarely publish in them.

In the second group we find non-economics journals like the *Jasss*, *Energy Policy*, and, further down the list, *Physica A* (Table 1). These journals highlight the frontier nature of economics ABMs as, despite our economic-oriented methodology, we still find non-economics journals. However, unlike the case of econophysics (Gingras and Schinckus, 2012, p.115) where *Physica A* is the main venue of publication, these journals are relatively secondary in terms of number of publications compared to the first group of economics journals. This statement remains true among the most cited journals (Table 2).

Finally, in a third group we have thematically-specialized journals: *Ecological Economics*, *International Journal of Production Economics*, *Journal of Environmental Management*, and

Journal	share
Journal Of Economic Dynamics & Control	8.86%
Journal Of Economic Interaction And Coordination	7.26%
Computational Economics	6.72%
Journal Of Economic Behavior & Organization	5.98%
Energy Policy	5.12%
Journal Of Evolutionary Economics	4.38%
Ecological Economics	4.06%
Jasss-The Journal Of Artificial Societies And Social Simulation	3.20%
International Journal Of Production Economics	3.09%
Journal Of Environmental Management	2.88%

Table 1: Venues of Publications of ABMs

Citations to	Number of Citations
Journal Of Economic Dynamics & Control	1193
American Economic Review	930
Journal Of Economic Behavior & Organization	704
Econometrica	516
Physica A	477
Energy Policy	476
Journal of Political Economy	430
Quarterly Journal of Economics	390
Nature	333
Journal Of Evolutionary Economics	308

Table 2: Most Cited Journals

further down the list, *Macroeconomic Dynamics* (Table 1). The most obvious dominating theme from these journals (especially while taking *Energy Policy* into account) is the question of the environment which is a first clue for a potential research theme in our corpus.

Studying the journals in which ABMs are published and cited by ABMs highlights two important results. First, while ABMs do not entertain a strong relationship with the more heterodox journals, it is not exactly part of the mainstream either. While authors cite mainstream economics research a lot, they almost never publish in the most influential journals of economics. Despite the fact that ABMs are often compared to experimental economics, behavioral economics, or econophysics as part of a general observation that mainstream orthodox economics is dead (Colander, 2000; Colander et al., 2004; Davis, 2019), ABMs are in a very different situation. For example, ABMs are less successful and less mainstream than behavioral economics in terms of access to top economic journals. However, ABMs are still more econ-oriented and accepted than econophysics (Gingras and Schinckus, 2012).

A second important observation is that despite our focus on a very narrow definition of ABMs in economics, we still find some links with non-economics journals. In addition to the fact that the economics journals publishing ABMs have a strong policy favoring interdisciplinary work, ABMs publications in economics cite (and publish in) some non-economics journals.

Finally, as hinted by some thematically oriented journals, ABMs in economics cover different fields that might entail heterogeneous epistemic goals and practices. In the next section, we explore this heterogeneity to investigate how the importation of ABMs in different contexts can lead to different ways to adopt ABMs in economics.

4.2 The Heterogeneity of ABMs

In the literature on ABMs in economics, we find a variety of ways to split the fields into sub-specialties (Table 3). Schinckus (2019) advocates for a classification based on methodological approaches. Metaphorical approaches favor bottom-up methods and macro-scale phenomena, where agents' behavior is not contingent upon economic or behavioral assumptions but relies on metaphorical concepts, such as thermal behavior or fluid dynamics. In contrast, deductive and abductive approaches incorporate behavioral assumptions. Classical rational agents in the former and a range of bounded rationality concepts in the latter. Other parts of the literature (Chen, 2012), prefer to categorize the field based on different paradigms that have diverse origins. These paradigms encompass ABMs with three types of origins: cellular-automata origin (e.g., zero-intelligence agents), economic tournament origin (e.g., iterated prisoner's dilemma tournament), and experimental economics origin (e.g., herding-based models). Finally, other reviews Squazzoni (2010); Hommes and LeBaron (2018) categorize the field by topics (or a mix of topics/methods) in which ABMs have been used: macroeconomics, finance, innovation, labor economics...

For our corpus, we used community detection to identify some of the most structuring research themes in ABMs. Given that our time frame covers almost 20 years of publications, with 10 years overlapping windows, we produced 12 bibliographic coupling networks each with its own detected clusters. This results in hundreds of clusters. To distinguish the

Paper	Areas, topics, methods, or paradigms identified
Tesfasion (2002)	- Learning and embodied mind - Evolution of behavioral norms - Bottom-up modeling of market processes - Formation of economic networks - Modeling of organizations - Design of computational agents for automated markets - Parallel experiments with real and computational agents - Building ACE computational laboratories
Squazzoni (2010)	- Industrial economics - Labour economics - Innovation - Macroeconomics - Financial markets
Chen (2012)	- Markets origin - Cellular-automata origin - Economic tournament origin - Experimental origin
Hommes and Lebaron (2018)	- Macroeconomics - Finance - Experiments - Networks - Other
Schinckus (2019)	- Deductive approach (rational ABM) - Abductive approach (adaptive ABM) - Metaphorical approach (bottom-up econophysics) - Phenomenological approach (top-down econophysics)

Table 3: The different specialties of ABMs economics in the literature

most structuring clusters from noisy-clusters produced by the algorithms, we connected our clusters intertemporally. If between two time windows, a cluster has more than 55% of its nodes going to another cluster, and that latter cluster is composed of more than 55% of nodes from the previous cluster, then these two clusters are automatically identified as the same cluster. While the content of the community might have changed between the two periods (something we will take into account as we zoom in on a particular time frame), they are considered to have a strong relationship and therefore part of the same intertemporal cluster.

This first process results in dozens of clusters, some that are very small or that do not survive more than a handful of windows are ignored. To get an overview of these dozens of clusters, we named the 12 biggest clusters and created meta-clusters to identify how they relate to each other. For example, we find multiple clusters that are clearly "finance". To find out how these clusters with similar content relate (or not) to each other, we created a network of the intertemporal relationships between our clusters. If many nodes go from one community to another between two periods, then we compute it as a link. We sum all the links between clusters and normalized them using cosine similarity. This results in one network with all relationships between clusters. We artificially cut off the weakest link,[2] and grouped related clusters with shades of similar colors. This results in an alluvial diagram with all individual clusters identified across all 12 networks. (Figure 1)

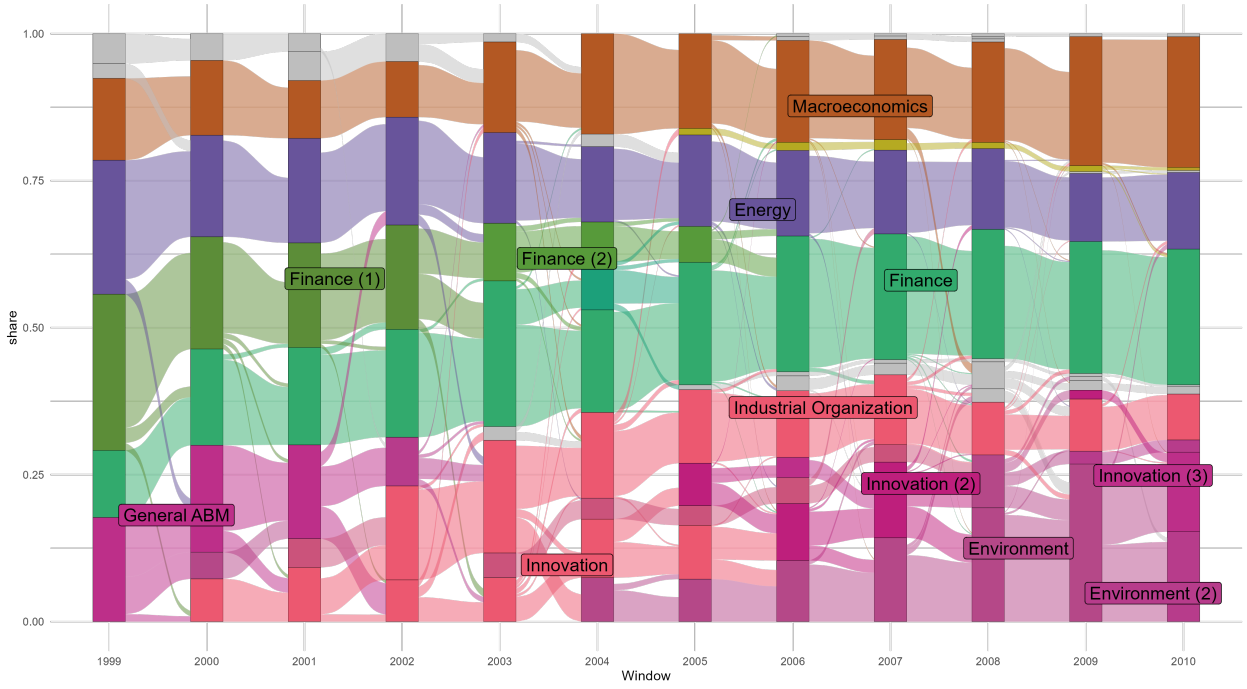

Figure 1: Intertemporal Communities

[2]We remove all links under 0.45. Given that all links are normalized between 0 and 1 by the cosine normalization, interesting cut-off thresholds tend to be between 0.4 and 0.5

We find three clusters that are both stable and important across all networks, and a fourth group of communities that regroups emerging and unstable research clusters. The first stable cluster is the Finance community in relation to the use of ABMs to study financial markets. In the early years of the networks, the Finance clusters are split in two, with one cluster being more Asian and US-oriented (in terms of authors' affiliations) and the other more European. It progressively stabilized to be one cluster around the 2006 window. The second important cluster is the Energy cluster which tackles energy markets with ABMs tools. Finally, the third stable cluster is Macroeconomics, in relation to agent-based approach of business cycles, growth, and general macroeconomics policy. These three clusters are the most structuring forces of ABMs models in economics over the time period studied in terms of stability and number of articles.

In the fourth group, we find a set of diverse clusters that emerged consistently across networks, but only a few appear to stabilize in the very latter periods: the Environment cluster in relation to ecology and environmental economics, the Innovation cluster about technology diffusion, and finally the IO/microeconomics cluster with a diverse set of articles about specific markets (e.g., labor, housing), market structure, and supply chain management.

Finally, we also find a variety of smaller clusters which we decide to ignore for the purpose of the articles because they are either too unstable (only exist for one time window) or too small (never more than 5% in any network). These clusters capture potentially important questions emerging in ABMs economics (e.g., the cluster "4k0nYRzH" is for example about pro-social behavior and ABMs in experimental settings), however, they are not part of a clearly established community in ABMs. While they capture some of the diversity of ABMs, they are marginal as stable research communities in ABMs economics.

Upon closer examination of the clusters identified as 'stable' and representative of the penetration of the economy by ABMs, we find that the epistemological status of ABMs vary considerably between different groups. The next step is then to investigate the content and practices characterizing these different clusters in more detail to better assess the degree of integration of ABMs into economics, but also their potential impact on the relationship between economics and other disciplines. The subsequent section will then proceed to examine the finance and macroeconomics clusters in greater detail.

5 Reforming Core-Oriented Interdisciplinarity: Finance and Macroeconomics

With Finance and Macroeconomics, we find two of the most structuring communities of ABMs in economics. By the 2010s, these two clusters were the two biggest ones, and by far the most economics oriented.

Quantitatively and historically, finance is one of the most dominating clusters in the networks of our corpus confirming then Tesfatsion and Judd (2006, p.xii) who already observed that "Financial economics is one of the more active ACE research areas". Up to the 2006-2015 network, finance is split between two clusters. If we count these two clusters as

Clusters	2001-2010	2006-2015	2010-2019
All Finance Clusters	25%	23%	23%
Energy	18%	15%	13%
Macroeconomics	10%	17%	22%
IO/Microeconomics	9%	11%	8%
Environment	/	10%	15%
Innovation	/	10%	14%

Table 4: Share of Clusters in Networks

one, finance is particularly predominant with 25% of the network in the 2001-2010 window, 7 points above the second biggest cluster for example (Table 4). In the 2010-2019 network finance is identified as a unique cluster, still predominant, although with a smaller margin with the second biggest cluster.

The macroeconomics cluster appear relatively small when compared to finance in the early 2000s. With less than 10% of the nodes in the network, macroeconomics was only the fifth most important cluster quantitatively. Moreover, in the early 2000s the attempts to have an ABMs approach to macroeconomics were closely related to the previous work on finance with, for example, some articles focusing on financial fragility (Gallegati et al., 2003; Gatti et al., 2005). The field of macroeconomics grew rapidly during the 2010s, and went from the fifth largest cluster with 10% of the network, to the second largest cluster, on almost equal grounds with finance, to 22% (vs 23% for finance) (Table 4). This makes macroeconomics the fastest-growing cluster over the time period studied as most other clusters (Finance, Energy) have decreased in relative importance.

At the Santa Fe, the early 1990s were dedicated to developing the "Santa Fe approach" (SFI Bulletin, Winter-Spring 1990, p.12), this included exploring a variety of directions with a focus on how complexity approaches depart from the neoclassical model (Fontana, 2010). Rapidly, finance emerged as an important topic. The efficient market hypothesis was seen as the consequence of economists using "inappropriate statistical techniques" (SFI Bulletin, Fall-Winter 1991, p.30). Multiple alternative approaches to explore were evoked by members of the Santa Fe such as models and statistical approaches from physics, but also from psychology as psychological states (e.g., mood swings) were believed to be important. In 1992, Blake Lebaron, one of the leading figures of finance ABMs at the time, took the direction of the program. Lebaron intended to "steer the program in a more empirical direction" with the theory of financial markets and time-series analysis as two of the three areas of priority (SFI Bulletin, Fall-Winter 1992, p.19).

Financial markets were a particularly fruitful research direction for members of the Santa Fe as they covered the market efficiency hypotheses and the rationality hypotheses. From a practical point of view, finance was a research field that had plenty of "curious puzzles" and a "wealth of data" to explore alternative models and methods LeBaron (2006, p.1190). This observation from LeBaron was shared more generally by other economists unsatisfied with standard theory like econophysicists (Jovanovic and Schinckus, 2013b,a) and behavioral

Reference	Journals	Share
Brock and Hommes (1998)	JEDC	33.5%
LeBaron et al. (1999)	JEDC	21.2%
Brock and Hommes (1997)	Econometrica	20.0%
Lux and Marchesi (1999)	Nature	18.8%
Gode and Sunder (1993)	Journal of Political Economy	18.4%
Lux (1995)	Economic Journal	18.0%
Arthur et al. (1997a)	Book Chapter	13.5%
LeBaron (2006)	Book Chapter	13.5%
Kirman (1993)	Quarterly Journal of Economics	12.2%
Hommes (2006)	Book Chapter	12.2%

Table 5: Most Cited References in the Finance Community (Share of Nodes Citing these References)

economists close to members of the program. Richard Thaler had his series of anomalies about financial markets published around the same time as the Santa Fe program (Thaler, 1987), and himself had noted the centrality of finance to convince economists to explore alternative research directions (Thaler, 2015, p.203). [3]. The 1990s witnessed an era of considerable advancement in the field of finance. These new developments challenged existing concepts, introducing numerous innovative methodologies derived from a convergence of behavioral, complexity, econophysics, and agent-based methodologies. The resulting approaches identified several anomalies and proposed a range of alternative approaches.

The program would lead to the publication of multiple seminal articles and chapters that would establish the foundation of ABMs models in Finance. In our networks, the most cited references clue us into some of the milestones of the field. At the end of the 1990s, ABMs economists managed to successfully publish some articles in some elite journals of economics such as the *Journal of Political Economy* (Gode and Sunder, 1993), *Econometrica* (Brock and Hommes, 1997) and the *Economic Journal* (Lux, 1995), but also in elite generalist journals such as *Nature* (Lux and Marchesi, 1999). The regular publication of Handbooks by the Santa Fe in multiple volume (Arthur et al., 1997b; Tesfatsion, 2006) also proved particularly fruitful in creating a common basis for the formation of a community (Table 5).

While finance was one important topic at the Santa Fe, macroeconomics did not exactly emerge as a specialty until later on. Indeed, stock markets had a dedicated research axis in the early 1990s but macroeconomics was understood as part of a larger approach to "technological innovation, macroeconomics, and industrial demography" (SFI Bulletin, Winter-Spring 1990, p.12). The objective was to mobilise the tools from complexity approaches in order to build a joint analysis of "three traditionally distinct economic subdisciplines" (SFI Bulletin, Winter-Spring 1990, p.11) namely, macroeconomics, industrial organization, and the demography of innovations.

Within the Santa Fe, this program had an unusually strong Italian influence with many

[3]We find some common interests between behavioral and ABMs economists as they shared common seminars (e.g., Santa Fe), journals (e.g., JEBO), or institutional affiliations (e.g., Carnegie, MIT)

2006-2015	2010-2019
Mauro Gallegati*	Mauro Gallegati*
Alberto Russo*	Andrea Roventini*
Domenico Delli Gatti*	Alberto Russo*
Giorgio Fagiolo*	Giovanni Dosi*
Andrea Roventini*	Luca Riccetti*
Herbert Dawid	Silvano Cincotti*
Edoardo Gaffeo*	Marco Raberto*
Giovanni Dosi*	Andrea Teglio*
Simon Gemkow	Herbert Dawid
Philipp Harting	Mauro Napoletano*

Table 6: Most Prolific Authors in Macroeconomics Clusters (asterisk indicates Italian economists)

investigators from Italian universities: Francesca Chiaromonte, Giovanni Dosi, and Marco Lippi from the University of Rome, and Franco Malerba and Luigi Orsenigo from the University of Milan for example. This significant Italian influence persisted throughout the 2000s and 2010s as confirmed by our network analysis. Among the 10 most prolific authors in macroeconomics clusters, 9 out of 10 are Italian Economists (Table 6). Among the top 10 most occurring institutional affiliations in the macroeconomics cluster of the 2010-2019 network, half are Italians, and with the exception of the Santa Fe Institute, all are Europeans (Table 7). Overall, around 40% of the articles in macroeconomics ABMs have at least one institutionally Italian-affiliated author.

Macroeconomists have very few publications in the top 5 journals of economics but we can mention a small 5-page article published by Lebaron and Tesfatsion in the *American Economic Review* (LeBaron and Tesfatsion, 2008) to promote the new approach to macroeconomics modeling. In this AER article, ABMs macroeconomics models are presented as new tools that complete standard approaches. ABMs "thrive in the tails of distributions where standard empirical models are likely to fail" despite potential limitations as "[i]t is quite possible that the usual reduced-form models will never be beaten" in policy-making (LeBaron and Tesfatsion, 2008, p.249). This presentation of ABMs macroeconomics is quite tamed when compared to the Italian approach of Gatti et al.'s2010 "Complex agent-based macroeconomics: a manifesto for a new paradigm" in which there is an explicit call "to replace the reductionist approach".

With the publications of multiple papers and programmatic writings, notably by Italian economists, the late 2000s became an opportunity for these ABMs macroeconomists to develop a specific approach to ABMs. Without denying their historical links with Santa Fe, these economists have also developed specific ideas on how ABMs should be used in economics, including in stronger opposition to standard macroeconomics. This development resulted from the particular institutional and sociological composition of ABMs in macroeconomics with a dominance of economists from Europe (and more specifically from Italy) who all shared a strong interest in disequilibrium approaches (Goutsmedt and Truc, 2023).

Institutions	Country
Marche Polytechnic University	Italy
OFCE (French Economic Observatory)	France
Sant'Anna School of Advanced Studies	Italy
Università Cattolica del Sacro Cuore	Italy
University Of Genoa	Italy
Jaume I University	Spain
Sapienza University of Rome	Italy
Santa Fe Institute	US
SKEMA Business School	France
Bielefeld University	German

Table 7: Most Occurring Institutional Affiliations in the Macroeconomics Cluster

For Dosi and Roventini (2017), this is the "Italian tradition" that "paved the way for the development of a new generation of macroeconomic agent-based models" in Italy. Dosi et al. (2017) characterize this Italian tradition by a general opposition to neoclassical economics and an interest in classical economists and political history (Dosi and Roventini, 2017, p.263). Nevertheless, it cannot be definitively stated that the Italian tradition was the primary factor in this community's receptivity to ABM approaches to macroeconomics. In fact, reverse causality cannot be ruled out. As previously mentioned, Dosi and other Italian economists were involved in the early years of the Santa Fe macroeconomics program. It is, therefore, unsurprising that the Italian economists at the Santa Fe Institute have left their mark on the research program on ABM in macroeconomics, given that they were instrumental in defining it. This Italian tradition persists to this day. It is evident that a crucial question remains unanswered: why were so many Italians involved in the Santa Fe Institute and in addition, so densely involved in the macroeconomic program? This is clearly a specific issue that goes beyond the scope of this document, but it seems to us that at least, it is now better identified and certainly deserves to be explored in greater depth.

While Finance and Macroeconomics have different topics and traditions, they share a common approach to ABMs from an interdisciplinary point of view. Interdisciplinarity can take a variety of forms. This includes the commonly accepted distinctions between the very large categories of multi/inter/trans-disciplinarity, but there are other kinds of typological classifications with more dimensions (cf. Klein (2017)). A first typological question relates to how much interdisciplinary research programs relate to the core of the discipline.

ABMs approaches have a particular orientation in relation to the core-periphery structure of economics (Fourcade, 2006; Davis, 2008). Davis (2008) distinguishes between traditional heterodox programs and mainstream heterodoxy. The former regroups all traditional heterodox approaches (e.g., marxist, post-keynesians), and is characterized by, among other things, an orientation towards the periphery of economics (they want to redefine economics rather than reform it) and a confinement to the periphery of the profession (they don't have privileged access to the best journals). On the opposite, mainstream heterodoxies (e.g., be-

havioral economics) want to change economics by reforming the profession, they are oriented towards integrating its core, and they are accepted as a legitimate part of mainstream economics Colander et al. (2004). Even if elements are imported from other disciplines, and eventually the frontiers of economics move, there is no disciplinary integration of economics into a larger new discipline (Grüne-Yanoff, 2016).

In the case of ABMs we find a particular situation. While ABMs in finance managed to publish a few articles in the top 5, this is not as much the case for macroeconomists. The few top 5 publications in finance highlight some of the successes of ABMs at the end of the 1990s, but we nevertheless find that the vast majority of articles are published in the more specialized journals related to complexity approaches in economics like the JEDC, JEIC, Computational Economics, and the JEBO. In addition, one can see that there is a clear asymmetrical relationship with the top 5: while most articles are published in specialized journals, many references are to top journals in economics and finance. This is particularly the case in macroeconomics ABMs where the most cited journals (with the exception of the ABMs journals) are the AER, the QJE, the JEP, the JPE, and Econometrica. In Finance, we find a similar list of journals to which we can add *Quantitative Finance*, *Review of Financial Studies*, and the *Journal of Financial Economics*.

The case of ABMs in finance and macroeconomics highlights then a tension regarding this distinction. The proponents of these programs do seem heavily oriented towards the core of the profession. They try to publish in them and managed to do it a few times (LeBaron and Tesfatsion, 2008; Colander et al., 2008). They heavily cite top journals, partly to criticize the literature (e.g., DSGE models), but also because top journals publish relevant literature for them (e.g., bounded rationality in behavioral economics, experiments, some ABMs). However, unlike behavioral economists, these ABMs economists do not have easy access to the top journals. In comparison, Kahneman published his first article in economics in *Econometrica* in 1979 and his following articles in economics were in the *American Economic Review* in 1986 (Kahneman et al., 1986), in 1990 and 1991 along with publications in the QJE and the JEP (Tversky et al., 1990; Kahneman et al., 1991; Kahneman and Thaler, 1991). In other words, already in the early years of the behavioral research program, behavioral economists published mostly in the top journals of economics. Just like experimental economists refused to create and publish in specialized by fear of getting "ghettoized" (Maas and Svorenčík, 2016, p.68), behavioral economists did not create or focus on dedicated journals to their approach, and instead published in elite journals.

Despite emerging during the same decade, with similar intents, most publications in ABMs finance and macroeconomics were confined to specialized journals. The status of these journals is nevertheless ambiguous; they are not historical heterodox journals, and some, like the JEBO, are even now recognized as top journals in their field. So one cannot conclude that publication media, chosen or constrained, confine ABMs to the periphery of economics. Clearly, ABMs are not considered as "traditional heterodoxies" but they are not exactly considered as part of the core either. This leads to an asymmetrical relationship with the core of economics (see Baccini et al. 2022), that ABMs economists rely on and want to reform, and field journals that confined ABMs to a handful of venues of publications in

Clusters	2001-2010	2006-2015	2010-2019	Trend
Macroeconomics	52.86%	24.42%	17.92%	↘
All Finance Clusters	25.19%	25.71%	24.25%	→
IO/Microeconomics	13.91%	18.71%	27.11%	↗
Energy	31.05%	27.82%	36.15%	→
Innovation	/	37.08%	40.8%	→
Environment	/	62.59%	62.75%	→

Table 8: Share of Citations to Non-Economics and Non-Management Journals

which authors have difficult access to top journals.

A second typological question relates to the relationship between economics and other disciplines within ABMs. We find that finance and macroeconomics are weakly interdisciplinary and not much oriented toward the frontiers of economics compared to other clusters. The share of citations to non-economics and non-management journals of our two clusters is generally between 18% and 24% (Table 8). While these numbers are relatively high compared to all economics (Truc, 2022b), they are relatively low compared to other clusters (e.g., Environment cluster around 63%). While finance remained stable, we find that macroeconomists are citing less literature outside of economics over time. In the 2001-2010 network, a few publications were not in economics journals (e.g., *Physica A*, *Progress of Theoretical Physics*), and articles rely heavily on references published in physics journals in relation to Zipf's and power law of firm sizes (Axtell, 2001; Gaffeo et al., 2003). After the 2010s, this reliance on outside journals completely decreased as macroeconomists established themselves in specialized journals in economics that became the main source of references for the field. Most non-economics citations are to generalist (e.g., *Nature*) and physics (*Physica A*) journals which denote a strong orientation toward methodological borrowing as these economists rely on methodological (Gilli and Winker, 2003; Tedeschi et al., 2012) and programmatic writing (Farmer and Foley, 2009; Fagiolo and Roventini, 2017) published outside of economics (e.g., *Physica A*, *Jasss*).

Using Klein's 2017 typology, we can characterize the interdisciplinarity of these specialties as methodological, instrumental, and critically core-oriented. These ABMs economists are confined to well-identified field journals that are characterized by the way they import ABMs and other complexity approaches in economics. Most actors of the field are economists, and in the case of macroeconomics, Italian economists. The knowledge transfer of ABMs is mostly about bringing new tools in economics to answer economics-oriented questions with a critical perspective on the core of the economics profession. These tools are the basis to reform the core of economics but, in practice, finance and macroeconomics do not challenge existing frontiers between disciplines. This situation contrasts with, for example, econophysicists (Gingras and Schinckus, 2012) who created a specialty mostly structured by physicists' concerns with economics. In that sense, macro and finance ABMs are similar to behavioral economists, who, while criticizing standard rationality models, do not explicitly challenge the existing disciplinary organization. The comparison is particularly relevant in

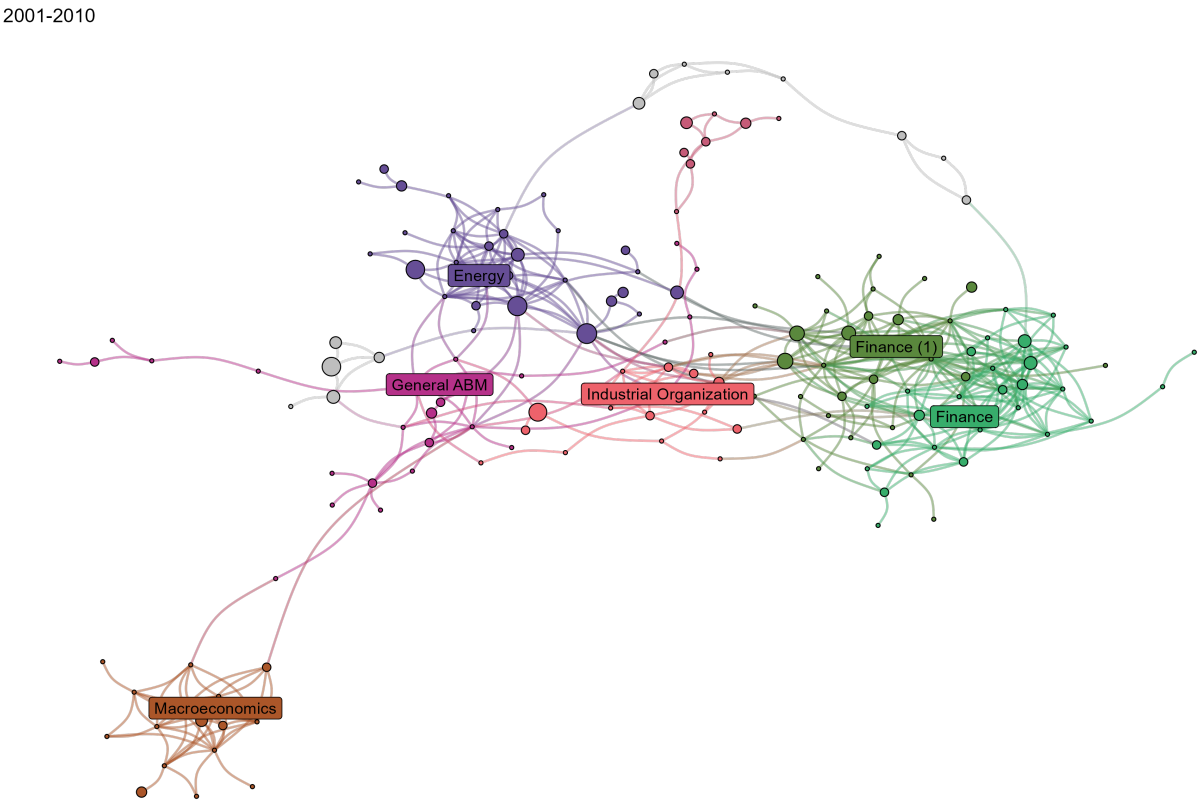

Figure 2: Bibliographic network of 2001-2010 publications

the fact that both behavioral and ABMs economists share a common top-field journal with the JEBO. However, we also find an important difference: both programs are oriented toward reforming the core of economics but ABMs remain, for the present time, confined to their sub-field with limited access to top journals when compared to behavioral economics.

This core-oriented approach is characteristic of Finance and Macroeconomics but we also find other forms of interdisciplinarity within ABMs economics, and it concerns fields that are not as strongly connected to the Santa Fe.

6 ABMs as bridge building and restructuring interdisciplinarity

Unlike the Finance and Macroeconomics clusters, the other notable clusters (Environment, Innovation, and Energy) of our networks are not economics core-oriented. While the Energy cluster was present and stable throughout the period studied, it decreased in importance from 18% of the network to 13%. At the opposite, the Innovation and Environment clusters emerged relatively late and grew to up to 15% of the network in the 2010s networks (Table

4).

A big way in which the Energy and Innovation clusters diverge from the two previous clusters studied is a relatively weak presence of economics. With around 30% to 40% of their references to non-economics and non-management disciplines, these two clusters are midway between Macroeconomics/Finance and Environment in openness to other disciplines (Table 8). If we only focus on economics references, the share of citations to the discipline falls to 55% in Energy, and 35% in Innovation compared to 67% in Macroeconomics. The interest for specialized ABMs economics journals (e.g., JEBO) and top 5 economics journals is also a lot weaker with most of the citations and publications in and to economics journals concern very specialized journals like the *Journal of Evolutionary Economics*, *Computational Economics*, *Energy Policy*, *Energy Economics*. We also find a variety of journals that are unique to these clusters reflecting their thematic specialties like *Applied Energy*, *Utilities Policy*, and *IEEE Transactions on Power Systems* for Energy, and the *Technological Forecasting and Social Change* for Innovation.

In both the Innovation and Energy clusters, important contributors are not economists. With 24% of its references to management, the Innovation clusters associate computer scientists and engineers (Eppstein et al., 2011), as well as physicists and organizations and management researchers (Kowalska-Pyzalska et al., 2014). In our 2001-2010 network, the most cited references of the Energy cluster were written by management and operations research scholars (Bunn and Oliveira, 2001), electrical engineers, and computational scientists (Nicolaisen et al., 2001). Unlike the two previous clusters, the most prominent institutional affiliations are to US- and UK-based institutions. This observation confirms that the field partly emerged from the restructuration of US and UK electric power systems in the mid-1990s (Tesfatsion, 2018, p.733). Reforms such as the New Electricity Trading Arrangements (NETA) in the U.K encouraged market-based decentralized systems for better valuation and allocation of electricity. The issue was not only economics as the trading of electricity involved major infrastructure issues for the power grids to remain stable. Unlike other types of markets, some major concerns were related to engineering questions, not economics ones.

The most striking example of this weak connection to economics is the Environmental cluster. With more than 60% of their references to non-economics/management journals, the Environment cluster is by far the less economics-oriented cluster (Table 8). While the Macroeconomics and Finance clusters can reasonably be characterized as Agent-Based Computational Economics, the Environment cluster is barely economics.

Another characteristic of these clusters is a weak historical connection to the Santa Fe economics program. Electricity market organization was not explicitly discussed as a specific research direction at the Santa Fe. According to Tesfatsion (2018, p.733), the interest of electrical engineers in economics only emerged at the end of the 1990s as exemplified by the case of Sheblé (1999) whose attention to auction market design and behavior was "unusual for a power engineering text at the time". Like in the case of Finance of Macroeconomics, engineers noted that "conventional economic modeling approaches have shown only a limited ability" when applied to these new electricity markets(Bunn and Oliveira, 2001, p.493). Some limits included market structure issues such as a limited number of actors in electricity

markets (few sellers and buyers of equal size), or game theoretical issues such as the fact that exchanges are discrete with few repetitions (not a repeated game leads to a lack of learning opportunities). In addition to these behavioral and economic issues, engineering problems added another layer of complexity that made ABMs approach particularly interesting for power systems researchers. These questions also led researchers interested in electric markets to deviate towards research that was further away from core economics concerns.

Similarly, the question of the environment was not particularly central to the economic program as the Santa Fe. Instead, it was developed at the SF under the guise of more interdisciplinary research programs such as "Project 2050: Transition to Sustainability" (SFI, 1993, p.9, fall). The goal of these programs was to promote general models, such as the "ECHO general-purpose modeling platform" designed to integrate models developed by "economists, evolutionary biologists, and ecologists as abstractions of real-world systems." (SFI, 1993, p.9, fall). Economics was only one piece of the puzzle but was not the spearhead of the ambition of the program.

As for innovation, it was rapidly identified as one key concept of the SF that should be tackled by ABMs especially because it was understudied "in classical economics" (SFI, 1994, winter, p.8). It was identified as one of the key components of the general economy, and as such, was understood as more generally part of macroeconomics modeling as exemplified by the work group "Technological Innovation, Macroeconomics, and Industrial Demography". It led to collaborations with well-known mainstream economists such as Hal Varian to build a "micro-founded model for an economy fueled by technological innovation." (SFI, 1991, winter). The subject of innovation emerged in two other work groups dedicated to "growth in cities" and "learning and innovation in organizations". Both groups had a more focused approach to innovation, not only as something that is part of macroeconomics processes but also as something that involves "flow of ideas" and "interactions between individuals" (SFI bulletin, 1991, fall-winter). However, we find that the literature within the innovation cluster has little connection to this research. Rather, the study of innovation within economics was mostly absorbed by the macroeconomics ABM literature which integrates innovation by the way it affects macro-variables. On the opposite, the innovation cluster is driven by researchers specialized in social simulations and working on economics topics but with little connection to the specific economics program of the Santa Fe. Thematically, the innovation cluster has a strong proximity to the environmental cluster with the second highest number of links between the two clusters (Table 9). this proximity highlights that, rather than being macroeconomics oriented (innovation as a source of growth), the innovation cluster is more concerned with environmental issues such as the adoption of green technologies (e.g., electric cars, smart grid). The innovation cluster is also characterized by a unique methodological approach with an evolutionary and network-based approach to innovation. This is particularly evident from the fact that the *Journal of Evolutionary Economics* is the most published and most cited journal and (Watts and Strogatz, 1998) on small-world networks and (Barabási and Albert, 1999) on scale-free networks are consistently the two most cited references, while also being unique to this cluster.

The interdisciplinarity observed within these three clusters differs greatly from the one in

Cluster 1	Cluster 2	Strength
Finance	Macroeconomics	0.07
Environment (2)	Innovation (3)	0.05
Energy	Industrial Organization	0.03
Energy	Macroeconomics	0.03
Energy	Environment (2)	0.02
Energy	Finance	0.02
Energy	Innovation (3)	0.02
Environment (2)	Industrial Organization	0.02
Finance	Industrial Organization	0.02
Finance	Innovation (3)	0.02
Industrial Organization	Innovation (3)	0.02
Innovation (3)	Macroeconomics	0.02
Environment (2)	Macroeconomics	0.01
Industrial Organization	Macroeconomics	0.01
Environment (2)	Finance	0.00

Table 9: Strength of relationship between clusters (cosine normalized)

the Finance and Macroeconomics clusters. Within the Innovation and Energy clusters, we find a bridge-building and applied approach to interdisciplinarity. Bridging economics, engineering disciplines, and computational sciences is applied toward the objects of interest with a strong interest in "real-world implementation" Tesfatsion (2018, p.761). For Energy, this is also visible in institutional affiliations with specialized universities like the New Mexico Institute of Mining and Technology and industry-oriented foundations or the Central Research Institute of Electric Power Industry. Contra to Macroeconomics and Finance, there is no larger programmatic writing or will to reform the core of economics theory and its tools. What is most often pointed out by the literature is the specificity of energy markets and how it requires different tools than the ones used by economists. The Environmental clusters share many characteristics with the innovation and energy clusters but to a more extreme degree and is better characterized as restructuring and critical interdisciplinarity. As argued by Farmer et al. (2015), the ambition of environmental research using ABMs is to bring together different research trends to create complex all-encompassing models that capture the interactions between innovation, specific markets (energy), macroeconomics trends and policies, as well as ecological systems. Economics is very much a background discipline that is only one element to better tackle environmental issues, and the epistemic tradition of economists is approached from a critical perspective. According to this view, climate energy policy should be based on a variety of ABMs specialties coming together: electricity market, macro-economic analysis, technology diffusion, etc...

As we have observed until now, while it might have been expected that the use of the same ABMs tools have created a sort of intellectual community, researchers using ABMs in economics belong to different sub-fields and are pursuing different objectives despite sharing

common concerns for economics questions. Consequently, any attempt to produce a unified general perspective is difficult to conceive in the short term. It is particularly difficult given that, even within ABMs economics, this concern has been noted and it is considered that the diversity of approaches or absence of standardization "hinders the readability and acceptance of ACE research efforts" (Weidlich and Veit, 2008; Tesfatsion, 2018, p.761).

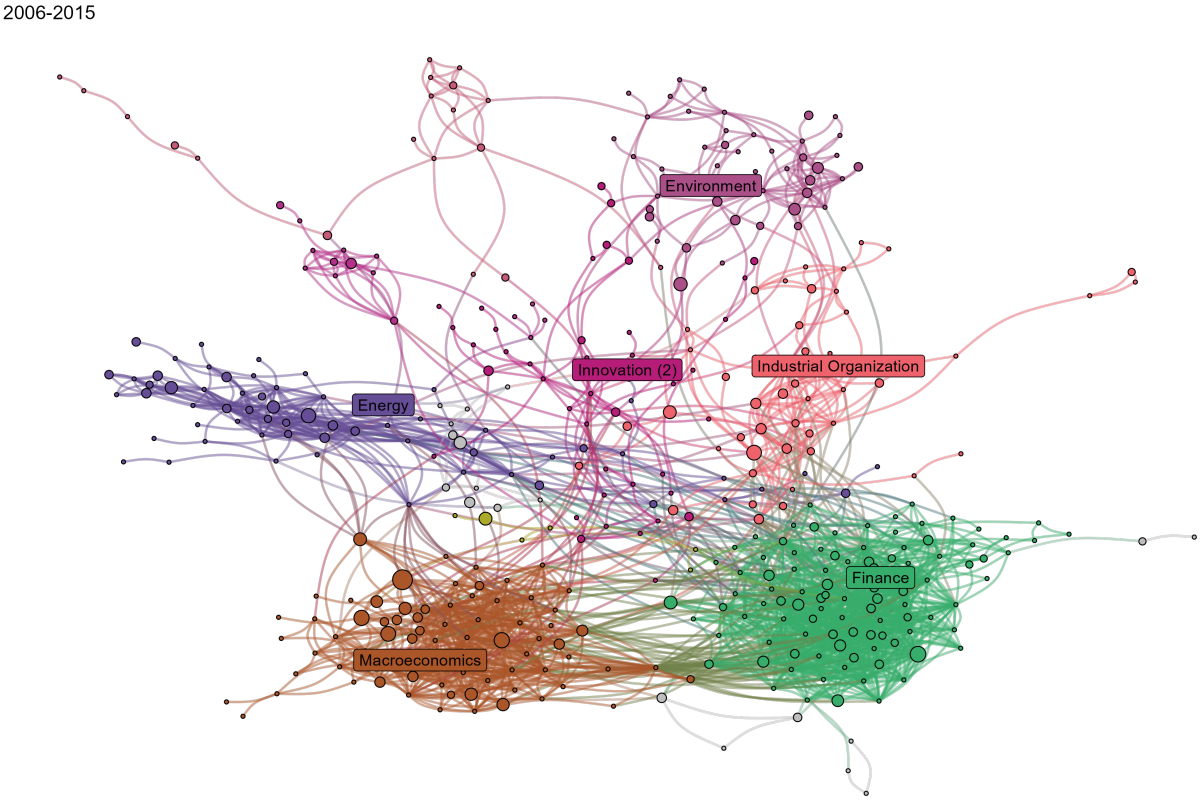

Figure 3: Bibliographic network of 2006-2015 publications

7 Conclusion

While agent-based computational economics is sometimes studied as a sub-field of economics or as a sub-specialty of social sciences ABMs, we showed that it eventually encompasses a variety of relatively heterogeneous approaches. These differences extend beyond research topics (macroeconomics, innovation), and manifest themselves in different approaches to interdisciplinarity and relationships to economics as a discipline.

Research communities on finance and macroeconomics were clearly structuring in the emergence of a dedicated sub-field of ABMs in economics. Their core-oriented approach can be characterized by a strong orientation towards economics and by the fact that interdisciplinarity is used as a way to transform the discipline. This sub-fields have asymmetrical

Figure 4: Bibliographic network of 2010-2019 publications

relationships with the top 5. While they are core-oriented and wish to transform economics, they rarely access the top generalist journals and remain mostly confined to specific journals that often publish ABMs papers. The economics program at Santa Fe played a pivotal role within these sub-fields but even more so in the case of macroeconomics. While the Finance clusters rapidly grew and internationalized beyond the initial network of the Santa Fe, research on macroeconomics resulted in the emergence of a specialization, with many authors based in Italy, and that seems to have associated the ABM-driven approach from the Santa Fe with a specific national approach to economics (Dosi and Roventini, 2017).

This approach to interdisciplinarity is not the only one we highlighted within ABMs economics as we find that other sub-fields are more challenging to the frontiers of economics. The first way frontiers are challenged is by building specialties around very applied topics that require collaborative efforts from different disciplines to tackle specific issues only partly related to economics. Research on innovation and energy markets is more applied-driven, both in its historical origins and the way it interacts with other disciplines. Within these fields, researchers from different disciplines often co-author papers together, and the role of economics and its core journals (i.e., top 5) is lessened while greater attention and prestige is given to specialized and technical journals (e.g., energy economics).

A second way frontiers are challenged is by drawing new frontiers and hierarchies between disciplines in terms of priority. In the case of environmental issues, economics is one important piece of the puzzle, but the discipline is only one among many. The issue is not how to use ABMs to reform environmental economics, but rather how ABMs can help bring together research from different disciplines by making their models more amenable to disciplinary integration within a larger environmental science (Farmer et al., 2015; MacLeod, 2018). The epistemic goals and tradition of economics thus become subject to environmental science goals and epistemic issues.

Our research argues against treating ABMs in economics as a unified field with a single history. Instead, it's a history at the crossroads of many histories, each deserving individual analysis.

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