Some Reflections on Financial Instability in Macro Agents-Based Models. Genealogy and objectives 1

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SOME REFLECTIONS ON FINANCIAL INSTABILITY IN MACRO AGENTS-BASED MODELS. GENEALOGY AND OBJECTIVES

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Some Reflections on Financial Instability in Macro Agents-Based Models.

Genealogy and objectives[1]

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Résumé. Ce papier analyse comment la macroéconomie multi-agents (MABM) qui a récemment connu un développement important, analyse la question de l'instabilité financière. Ce papier focalise l'attention sur deux communautés de chercheurs qui, au sein de ce paradigme, contribuent aujourd'hui plus spécifiquement à cette question. Nous examinons leurs fondements analytiques communs, notamment via les influences partagées issues de programmes de recherche antérieurs, ainsi que leurs stratégies de modélisation respectives et montrons ainsi comment ces dernières les conduisent à définir des objectifs quelque peu différents.

Abstract. This paper analyses how the macro agent-based literature which developed intensively during the last decades, analyses the issue of financial instability. This paper focuses its attention on two specific researchers' communities which, within this new paradigm, specifically emphasize this question. We examine their common analytical foundations, how they have been influenced by anterior research programs, and we distinguish their modeling strategies and how these distinct strategies led them to follow somewhat different objectives.

Mots clefs. Macroéconomie multi-agents, instabilité financière, fondements microéconomiques, CATS, K&S, Minsky, Leijonhufvud, Stiglitz.

Keywords. Macro agent-based models, financial instability, microeconomic foundations, CATS, K&S, Minsky, Leijonhufvud, Stiglitz.

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I. Introduction

The 2008 financial crisis has greatly increased criticism of the capacity of modern macroeconomic models to deal with large-scale crises and financial instability. Dynamic stochastic general equilibrium (DSGE) models are criticized for their core assumptions which assume all coordination issues as resolved, and enable an exclusive focus on the behavior of optimal dynamics[3] but hinder our understanding of how relatively small shocks can generate a large scale crisis. In the years following the 2008 crisis, macroeconomic agent-based models (MABMs) [4] came to be seen by many as directly challenging DSGE models in relation to this issue. This challenge takes both direct and indirect forms, and the arguments culminated in 2018 with the publication of two Special Issues in the *Oxford Review of Economic Policy* and the *Journal of Economic Perspectives*[5]. The present paper sets out not to discuss the relative merits of DSGE models and MABM in general, or to analyze the capacity of DSGE models to deal with financial issues[6]; rather it focuses on the contribution made by MABMs to our understanding of financial instability (and subsequent macroeconomic volatility). Thus, following a discussion of the different MABMs communities, we identify the various analytical (historical) roots[7] underlying the MABMs' research program, and the lines of research explored to deal with large-scale crises and financial instability. We conclude with some remarks about the possible consequences of those developments on the future of macroeconomics.

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[3] Cf. Colander *et al.* (2008).

[4] Agent-based models (ABMs) is the term used by several different disciplines. Agent-based computational economics (ACE) models are a specific application of an ABM. ACEs include a variety of models, essentially FABM (financial agent-based models) and MABM (macro agent-based models). All of them stem from the complex economics contribution(s) initiated for the most part by the Santa Fe Institute (cf. Fontana 2010). In this paper, we focus on MABM.

[5] Respectively noted Symposia (2018a) and (2018b).

[6] See Claessens S. and A. Kose (2017) for a survey of financial frictions, and Benes *et al.* (2014) for an examination of DSGE and financial crises and Trautwein (2021) who shows how DSGE models investigate the role of financial frictions more intensively, and the conclusions reached by these authors.

[7] Dosi and Roventini (2017) examine the reasons for the rapid diffusion in Italy of the MABM approach. In doing so, they provide some interesting links between current Italian MABM groups and various Italian political economy traditions which might explain why Italy seems to be such fertile ground for the introduction of these new approaches. However, they do not provide a systematic analysis of these models' various analytical roots which is what we aim to do in the present paper.

The paper is organized as follows. Section 2 briefly describes the theoretical context in which MABMs emerged. Section 3 identifies previous research programs which to a greater or lesser extent have influenced the current MABMs' research agenda. Section 4 examines how financial instability is addressed, and emphasizes the specificity of the different MABMs' modeling strategies. Section 5 concludes with some initial reflections on the status of those models and the degree to which they are considered a serious challenge to DSGE models in economic policy.

II. A brief history of the emergence of Agent-Based Macroeconomics

It is recognized that MABMs may in part be an expression of the resistance against the diffusion of DSGE models[8]; however, this is not to reduce the importance of their own research agenda. In this section, we briefly describe the theoretical underpinnings of the recent MABM microfoundational program.

Traditional critiques in a new favorable context.

General equilibrium (GE) approaches[9] support the idea that markets are inherently stable, a dynamic property which is linked strongly to their being built on "sound microeconomic foundations"[10]. This view was propounded in the early 1970s by Robert Lucas who later defined his goal as aimed at reincorporating "aggregative problems such as inflation and the business cycles within the general framework of 'microeconomic' theory" (Lucas 1987: 107). The main justification at the time for the "hyper-rational, self-interested agent typically used in standard macro models was that it was consistent with the characterization used in micro theorizing" (Colander *et al.* 2008: 236). According to this view, there are no macroeconomic phenomena which cannot be modeled (and then explained) by microeconomics, and consequently, aggregate macroeconomic variable dynamics are

[8] For a detailed discussion of the possible mutual influence between DSGE and MABMs see Dal Pont *et al.* (2021).
[9] Here, we are thinking of the equilibrium macroeconomics developed along New Classical School lines.
[10] The relationship between macro- and micro-economics has a long history; however, today's "microeconomic foundations" refer strictly to methodological individualism (cf. Duarte and Lima 2012).

identical to those related to a single "standard"[11] microeconomic agent. Clearly, this removes the need for any distinction between micro and macro (Lucas 1987: 107-108). Although this methodological turn was triggered by Lucas's seminal contribution, it remains a pillar of even the most recent macroeconomic models, i.e. DSGE models[12].

This (specific) conception of macroeconomic microfoundations overlooks the various ways in which the micro and macroeconomic levels are intertwined[13] and has been attacked regularly:

> it is of no use looking at some 'representative individual' in order to understand what will happen at the aggregate level. You would not imagine looking at the behaviour of a representative ant if you wanted to predict the evolution of the activity of the nest. In this view aggregate activity is not a blown-up version of individual behaviour. The passage from micro to macro is more complex than a simple adding up of independent individuals. (…) In economics, if we are interested in macroeconomic relations concerning the reactions to changes in various aggregate variables, we should not start at the level of the isolated rational individual. (Kirman 2011: 19)

Indeed, if we cease to consider individuals in isolation then if their interactions matter, *emergence* happens[14], and logically the "standard" aggregation method becomes inappropriate. This is an old question whose proper modeling (and simulation) was made possible only when economics started to borrow tools from complex systems analysis[15]. This research program was launched largely by the efforts of the Santa Fe institute in the 1980s[16]. Economists who adopted this approach considered that both the empirical evidence and the experimental results show that aggregation can generate regularities: "quite simple and not hyper-rational individual rules when aggregated become well shaped: regularities emerge from individual 'chaos'" (Delli Gatti *et al.* 2008a: 1). This led to the

[11] "By 'standard' microeconomics, we mean microeconomics founded on rational individuals i.e. based on a selfish *Homo Oeconomicus* who makes axiomatic-defined rational calculations aimed at maximizing a context-independent utility function" (Delli Gatti *et al.* 2011: 2).

[12] It is commonly assumed that DSGE models represent the current consensus which mixes the core New Classical School approach with New Keynesian elements. For more details of this mix, see de Vroey (2016) or Duarte (2015).

[13] Cf. for instance Hoover (2012) for a detailed exposition of the three main *Microfoundational Programs* or Backhouse and Boianovsky (2012) for a history of disequilibrium microeconomic foundations.

[14] Emergence occurs when an entity is observed to have properties which its individual parts on their own do not have. Also, these properties emerge only through the interactions among these parts. For a more detailed discussion, see the introduction in Delli Gatti *et al.* (2008a).

[15] We understand complex systems analysis as related mainly to two domains: non-linear dynamic systems and complex adaptative systems, both used to produce endogenous dynamics, networks models, *etc.*

[16] Cf. Arthur (2014).

idea that rather than focusing on "what individuals think and do", an alternative position would be to develop "micro foundations (that) might well mean how the macrostructure of the beehive influences the distribution of the behaviors of the bees. A sort of macrofoundation of the micro" (Dosi and Roventini 2019: 3). This constitutes a foundational argument against methodological individualism: "Any meaningful model of the macro economy must analyze not only the characteristics of the individuals *but also the structure of their interactions*" (Colander *et al.* 2008: 237, emphasis added).

Gradually, larger numbers of economists began to explore this alternative modeling strategy on the basis that it might be shown to be a better guide for policy makers[17], a growing tendency after the failure of DSGE models to explain the 2008 crisis and the subsequent recession. There were calls (Colander *et al.* 2018) for an "empirically based macroeconomic model" *i.e.* for a model which although a reduced form of the observed economy would nevertheless be able to accommodate some of its essential elements and characteristics:

> What must be refused is not reductionism per se, that is the idea that to understand a complex system we need an adequate description of the individual characteristics and of the network of interactions and its constituents, but methodological reductionism in its strongest form, according to which 'the whole is simply the sum of the parts' [reference here to Dawkins (1976)]. On the contrary, in a complex system, the whole constitutes something which is *more and different* than the mere linear combination of its constitutive parts. (Delli Gatti *et al.* (2011): 6) (original emphasis).

In the context of the 2008 crisis, one of the most salient failures of DSGE models was their inability to address the issue of instability. More generally, what was criticized was their contribution to the idea that "free markets" are fundamentally stable in *every circumstance* such that a single unique model can be applied to all possible situations, that was attacked[18]: in other words, "Much that is true when the economy is stable ceases to be true when it is not" (Leijonhufvud, 2014: 763).

[17] The speech delivered by Jean-Claude Trichet to the European Central Bank Conference (Frankfurt, November 18, 2010) is an example of the sudden interest of policy makers in MABMs: "The atomistic, optimizing agents underlying existing models do not capture behaviour during a crisis period. We need to deal better with heterogeneity across agents and the interaction among those heterogeneous agents. (…) Agent-based modelling dispenses with the optimization assumption and allows for more complex interactions between agents. Such approaches are worthy of our attention".

[18] The New Classical School developments have resulted in most economists losing interest in studying stability properties. However, it has been demonstrated that under reasonable informational assumptions, there is no adjustment process able to guarantee the existence of a convergence to equilibrium (Kirman 2016).

Nevertheless, the growing influence of DSGE models buoyed by the context of the *Great Moderation*, led economists, bankers, regulators and policy makers to disregard the possibility of serious systemic instability. The pre-crisis DSGE models say very little about agent heterogeneity[19], and nothing about scaling effects or coordination issues, all elements that many economists consider likely played a major role in the 2008 economic crisis and the subsequent recession. When the crisis forced economists to reconsider the soundness of their modeling strategy, MABMs found new support, and in recent years their results and conclusions have become increasingly widespread[20].

A Research program.

Based on agents' heterogeneity and decentralized coordination mechanism(s), MABMs can deal explicitly with coordination issues and disequilibria dynamics. These elements naturally pre-disposed the MABM literature to focus on (financial) instability issue(s) to try to *explain*[21] (and not just to *mimic*) large scale crises *i.e.* the essence being to understand how relatively small shocks are at the origin of deep downturns in order to understand in turn the salient disproportion between cause(s) and effect(s), between shocks and propagation[22].

The aggregate properties of such an economy are obtained by summing the microeconomic dynamics of heterogeneous agents, i.e. macroeconomics from the bottom-up[23]. The heterogeneity applies to several agent dimensions (individual behaviors). It is generally assumed that agents are linked through their social interactions, through markets or via networks. Their interactions tend to follow simple behavioral rules which reflect bounded rather than perfect individual rationality[24], and are based on local information. Agents use decision-making heuristics which enable learning and adaptive behaviors. A system is considered *complex* if the highest level is not the result of an

[19] Despite several previous attempts, the incorporation of heterogeneity in DSGE models became a major objective mainly after the crisis.
[20] However, the increased number of papers does not indicate cross-fertilization with DSGE models. This is a different issue which is examined in Dal Pont Legrand *et al.* (2021).
[21] Cf. Dal Pont Legrand and Hagemann (2019).
[22] Cf. Stiglitz (2015) for a detailed discussion.
[23] This is the title of Delli Gatti *et al.'s* 2011 book.
[24] Some (M)ABM models are based on a rational expectations hypothesis.

aggregation process but rather emerges from the set of interactions among multiple agents. As a result of these interactions, (M)ABMs can be characterized by externalities, non-linearities and dynamic processes with positive feedbacks. Logically, MABMs have come to represent an opportunity for heterodox theories to benefit from explicit microeconomic foundations. Nevertheless, it should be remembered that ABM are only "tools": they can co-construct theories but "by definition" are not core elements of a single specific approach[25].

III. Understanding (Macro-)Financial Instability: old roots for new microeconomic foundations

As emphasized above, MABMs are founded on renewed microeconomic foundations. As this research program became more substantial, it attracted many economists including a few who were already working on instability issues within different theoretical traditions so that the development of (M)ABMs provided an opportunity to revive older ideas and concepts. For some MAB modelers, search for the microeconomic foundations of macroeconomic financial instability was the main objective[26]; for others it was one of the useful ingredients which allowed a better understanding of economic dynamics[27]. Eight MABM families can be identified (Dawid and Delli Gatti 2018); however, in this paper, we focus exclusively on two that directly or indirectly address the instability issue in relation to the functioning of the financial sphere, namely K&S and CATS (see fn **Erreur ! Signet non défini.**)[28]. Before discussing the specificity of their respective contributions to financial instability, we would emphasize their common roots in Axel Leijonhufvud's great influence and commitment to heterogeneous interacting agents.

[25] For instance, see Heise (2017) for a characterization of mainstream complexity economics.
[26] Cf. the work initiated by Domenico Delli Gatti and Mauro Galegatti, a research program clearly inspired by Minsky.
[27] Cf. the K&S models.
[28] It should be noted that among the various macroeconomic research programs based on ABM, the so-called AGH (Asharf, Gershman and Howitt) research program is not without connection with the literature we examine. Indeed, this program was strongly influenced by Clower and Leijonhufvud; so that, similar to as other MABMs, the approach is linked to several of Leijonhufvud's contributions (1977, 1986, 1993, 1997, 2014). Moreover, Howitt is a member of the scientific board of the Trento Summer school created by Leijonhufvud. However, those models (AGH 2016, 2017; and Howitt 2012) do not emphasize financial instability but concentrate more on money and coordination.

Leijonhufvud's contribution to the search for disequilibrium microfoundations is well-known and strongly associated to the work of Clower[29]. However, his contribution to the introduction of complexity in economics has been so far rather neglected. He was a member of the UCLA Center for Computable Economics, and later was a prominent figure at the Trento university[30] where a group of economists began exploring the first ABMs. While Leijonhufvud never developed a specific computational model, he had a definite influence and tried to unite MABM-sympathizers to work on the same agenda[31]. His approach to computational economics was that he saw it as a possibility to explain how individuals for whom the equilibrium price vector initially was unknown, could coordinate in order to identify it: "(T)the economy should be looked at as a machine that has to compute the equilibrium" (1993: 7)[32]. So clearly, Leijonhufvud[33] paved the way to new microeconomic foundations[34] which could explain how decentralized (or poorly coordinated) economies work.

Heterogeneous interacting agents are clearly at the origin of endogenous business cycles dynamics. In recognition of their Schumpeterian inspiration, CATS and K&S models build on the concept of aggregation which explains business cycles as resulting from "the complex interactions of firms and industries (a procedure reminiscent of Schumpeter, 1939) in which small shocks and endogenous elements coexist" (Delli Gatti *et al.* 2008a: 2). Business cycles economists generally felt challenged by the recurrence of upturns and downturns in aggregate output and it is possible to distinguish two approaches to these problems. The first is equilibrium-based, and considers that cycles analysis should be interpreted in the context of the decomposition between impulse and propagation, a research program that goes back to Slutsky (1927) and Frisch (1933) and extends to present day DSGE models.

[29] Cf. Backhouse and Boianovsky (2013) or de Vroey (2016).
[30] Axel Leijonhufvud was appointed Professor of Monetary Theory and Policy at the University of Trento in 1995 and later founded the Trento summer school in Adaptative Economic Dynamics.
[31] This point was described by Domenico Delli Gatti and Hans Michael Trautwein (who both occasionally participated to the so-called "Trento Group") in separate interviews held in 2020.
[32] On this point, he refers to Goodwin (1951: 1-2) who argues that it now seems permissible "to regard the motion of an economy as a process of computing answers to the problems posed to it".
[33] See Leijonhufvud (1977, 1986, 1993, 2014) and Colander *et al.* (2008).
[34] See Dosi's tribute to Leijonhufvud in *Trento Summer School. 19 years with a passionate teacher* (p. 45). https://event.unitn.it/aed-summerschool/libro_trento_summer_school.pdf.

The second approach is based on disequilibrium and/or non-linearities (along the lines of Kaldor or Goodwin) and considers regular oscillations as endogenous phenomena. While clearly anchored in the impulse/propagation tradition, DSGE models are nevertheless at the origin of an increased overemphasis on shocks[35]. As emphasized by Stiglitz (2015), this neglect of a propagation mechanism hindered their ability to explain how small shocks can produce large fluctuations, a point on which they are clearly challenged by MABM

Indeed, proponents of MABMs consider that if all these approaches lead to deadlock, this is because none of them is appropriate to analyze the "interaction between statements at the microeconomic level in terms of behavioral rules and aggregate categories, like income, expenditures or savings" (Delli Gatti *et al.* 2008a: 3). Although these researchers do not doubt that individual behaviors are at the origin of fluctuations, the behavior of the whole system is different from the behavior of any one of its constitutive elements: heterogeneity and interactions were considered the two key elements of the CATS and K&S research programs. Since heterogeneity has been proven empirically to be a remarkable source of financial fragility, CATS extended Minsky's research program, building on heterogeneity and agents' interactions. The K&S program uses this heterogeneity in various ways: for instance, firm as well as expectations heterogeneity are at the origin of financial fragility and this way, introduce a Minskyan dimension.

Foundations of K&S (Keynes and Schumpeter)

The K&S research program originated in Santa Anna School of Economics in Pisa, initiated by Giovanni Dosi and driven by various combinations of co-authors[36]. Its Schumpeterian influences are clear certainly partly due to Dosi's personal research trajectory. The models are based on two key

[35] See Dal Pont Legrand and Hagemann (2019) for a discussion of the relative weights of shocks and propagation over the evolution of business cycles theories.
[36] Dosi *et al.* (2008, 2010, 2013, 2015, 2017, 2019, 2020).

elements identified as Keynesian demand/supply side interactions and Schumpeterian theories of technology-fueled economic growth. A financial amplification *via* credit cycles was introduced into this combination of elements.

Interconnection between the demand and supply sides. The main objective was to provide support for the role of long run (not just short run) demand dynamics which in turn, prompted the reemergence of the need for countercyclical policies. More precisely, K&S develops a sort of Schumpeterian endogenous growth model enabling examination of both long-run growth and short-run fluctuations:

> Business cycles are endogenous and have a genuine Keynesian origin. The production and investment choices of firms can lead to coordination failures in the goods markets which in turn affect aggregate output and unemployment dynamics. (Dosi and Roventini 2017: 9).

Depending on the favorable coincidence between on the one side innovative exploration of new technologies and on the other side (sufficient) demand, Dosi and Roventini identified two possible distinct growth regimes characterized by different short-run fluctuations and unemployment levels.

The Minsky connection. Although avoiding an overwhelming focus on the Minsky connection[37], K&S clearly introduces Minskyian elements[38], *i.e*. a credit cycle hypothesis. Banks' activities are procyclical: they support firms' development and allow leveraged activities. Conversely, during recessions, they drastically reduce the availability of credit at a time when firms most need it. The survival probability of those firms then decreases and default-loan losses outweigh banks' net worth. The spread of this scenario results in a banking crisis and governments generally being forced to offer bail-outs. However, as the 2008 crisis shows, this does not avoid a "credit crunch", and the large public deficits can lead to a sovereign debt crisis.

Schumpeter meeting Keynes? A growth cycles dimension. Although the modeling strategy is different, this research program has much in common with Stiglitz (1993). Stiglitz built a sequential rather than an ABM such that as demand decreases (recession), revenue and bank credit also decrease.

[37] Minsky (1986).
[38] See Dosi *et al.* (2015, 2020).

This forces firms to reduce the amounts of resources they allocate to R&D which in turn reduces the expected growth rate. Joint analysis of growth cycles means that this approach can be used to examine the impact not only of monetary or fiscal policies but also of technologies and industrial policies, and in each case, enables investigation of the short- and long-run consequences. All economic policies (fiscal, industrial, monetary, etc.) that dampen fluctuations have long-run impacts: dampening fluctuations smooths investment and production over the business cycles and fosters R&D and eventually growth. Thus, to some extent Keynesian countercyclical policies are compatible with Schumpeterian policies[39]. This approach underlines the inefficiency of austerity policies which deter growth and are self-defeating since they do not work to stabilize public finances[40].

Roots for CATS (Computational AdapTive System)[41].

Complexity economics. In the pre-CATS era, the tendency was to refer to "complex dynamics" with implicit references to chaos dynamics. The pioneers of this (vast) program on (endogenous) complex economic dynamics include Goodwin and Day. They proposed mainly macroeconomic models with no microeconomic foundations, which were highly parameter sensitive and difficult to validate empirically. Those models did not easily allow theoreticians to draw economic policy conclusions, and despite their merits, they were mostly ignored by policy makers. However, in the 1980s – promoted in part by the Santa Fe institute, and especially in the 1990s, agent-based computational economics (ACE) models were developed and shifted the emphasis from the macro to the micro level of analysis[42]. At this time, Delli Gatti and Gallegati were developing models based on network analysis and non-

[39] Concerning economic policy, business cycles and growth in Schumpeterian analysis see Dal Pont Legrand and Hagemann (2017a). In this paper, Keynesian and Schumpeterian countercyclical or stabilizing economic policy are clearly distinguished. In relation to Schumpeter's notion of the "recuperative powers of capitalism" and its differences with the modern notion of "productive recessions", see Dal Pont Legrand and Hagemann (2017b).
[40] See Dawid and Delli Gatti (2018) and Dosi and Roventini (2017) on this point, and for a more detailed accounting of the economic policy implications of the K&S approach in general see Fagiolo and Roventini (2012).
[41] We refer here to Battiston (2009), and to a series of his papers with different co-authors Delli Gatti *et al.* (2005, 2006, 2007, 2008a, 2008b, 2009, 2010a, 2011, 2012) and Assenza *et al.* (2015, 2019).
[42] Delli Gatti *et al.* (2008a: 8) use the same argument.

linearities[43], and were in contact with the Santa Fe institute[44]. There are various reasons for this rather sudden diffusion of these new models. It is undeniable that ABMs benefited from the development of new computational tools which were accessible to non-specialists unfamiliar with programming languages[45]. However, although necessary these technical conditions are not sufficient to explain the sudden emergence and development of ACE models. Our intuition is that these developments were driven by the parallel evolution of the economics of information which increased interest in research into agents' interactions; for instance Delli Gatti *et al.* (2008a) among others refer explicitly to the connection with the economics of information.

Hyman Minsky and financial fragility[46]*.* Hyman Minsky had a direct influence on the CATS program proposed by Domenico Delli Gatti and Mauro Gallegati[47]. Specifically, these latter were seeking an appropriate way to reintroduce Minsky's financial fragility concept within a model. Intuitively, the mechanism leading to financial fragility is that during a phase of economic prosperity, leverage builds progressively, exposure to (credit) risk increases and the system becomes extremely fragile meaning that a relatively small shock can have huge consequences. These ideas were proposed and developed by Hyman Minsky in the 1970s and 1980s but could be even more relevant in today's context of high(er) connectivity within the banking and financial network, which causes the significance of exposure to risk to increase. In the current economy, there is almost no chance that a shock will be confined to a limited part of the network. It should be noted that, in order to capture financial fragility, the CATs program investigated different mechanisms with the result that it uses a set of different

[43] Despite some evident merits, those tools were suffering from limitations: network modeling tools (at least in economics) were considered as rather "mechanical", while non-linear dynamics were difficult to validate empirically.

[44] Cf. Interview with Delli Gatti in January 2018 when he confirmed that both he and Gallegati visited the Santa Fe Institute in 2004 where they also met Farmer. At this time, almost certainly due to his investment in Econophysics, Mauro Gallegati was convinced by the applicability of complexity and ABM tools to his and Delli Gatti's joint research program.

[45] Sophisticate programming languages are still used but software such as NetLogo requires no specific *ex ante* knowledge which boosted the popularity of this modeling tool.

[46] Cf. interview with Domenico Delli Gatti conducted by Muriel Dal Pont (January 2018, Milano).

[47] Mauro Gallegati was awarded his PhD degree in 1989 from Marche Polytechnic University ; his supervisor was Hyman Minsky.

models (although they have some common fundamental elements) while so far, the K&S research program is based essentially on one core model which is applied (and adapted) to different issues.

Keynesian roots. Demand is an important element of the CATS model. This introduces a Keynesian flavor but this is not the most salient feature of the model which is focused on source(s) of financial instability and their macroeconomic impact. However, it is clear that these models and some post-Keynesian models apply common agent behavioral rules under uncertainty so that to some extent, the (new-)Keynesian connection, apart from the already mentioned Leijonhufvud influence , is related to the treatment of information.

Indeed, the economics of information owes much to the contributions of Greenwald and Stiglitz (GS)[48] with Joseph Stiglitz a regular co-author on MABM papers[49]. We can identify two distinct channels of influence. First, following GS (1987, 1990, 1993), Delli Gatti and Gallegati (DGG[50]) envisaged a GS style financial accelerator model to explore the consequences of the degree (and distribution) of agent heterogeneity for their GS type financial fragility. Since agents possess "local" information, imperfect information is a crucial element in their model. Also, since prices cannot reflect all the relevant information, agents are led to interact outside the price system. As in GS (1990), DGG modeled a leveraged aggregate supply, and again as in GS (1993) this meant that the probability of bankruptcy was incorporated in the firm's profit function. Thus, the model takes account of risk - uncertainty, and also the producer's realization that its future depends not only on its actions but also on the actions of others. Second, building on Stiglitz and Greenwald (SG) (2003), the emerging CATS team published three NBER working papers co-authored with GS: Battiston *et al.* (2009) and Delli Gatti *et al.* (2007, 2008b). Later, we can see the influence of SG (2003), mainly through the way they analyze the link between money and credit, and the subsequent capacity of credit to stabilize the economy.

[48] We would not want to suggest that Akerlof made no contribution to the theory of information but the CATS program does not refer explicitly to his work.

[49] Stiglitz is a regular co-author of CATS papers. He met Mauro Gallegati in 1989 (cf. interview of DDG January 2018) and contributed to business cycle models and network financial analysis. Recently he has published on K&S (see Dosi et al. (2020)).

[50] DGG refers to the work produced by these two authors independent of the larger CATS team.

Their 2003 book explores the functioning of a credit-based economy. They emphasize how credit differs from other commodities in being based explicitly on information and default risk. They analyze the consequences in terms of economic policy objectives and efficiency. This led SG (2003) to model other types of agent financial linkages in addition to the traditional lender/borrower links. In these models, relatively small disturbances can weaken large populations, add to the increasing financial fragility of the entire system and amplify shocks to the system. SG's (2003) monetary and fiscal policy conclusions are both innovative and revive forgotten views. However, at this stage their work did not constitute a "complete" network analysis: the linkages among agents were given so the model was mainly static and lacked economic motives. Because the microeconomic foundations of the SG framework were based on heterogeneous interacting agents, it became a candidate for ABM applications. The first paper coauthored by individuals from these two communities was published in 2006[51].

This section has examined how ABM benefited from long-established research programs. This supports the idea that ABM are primarily and mainly tools that can be exploited by various research agendas. This is not to minimize their theoretical contribution but rather to show that it may depend on the context in which they are mobilized. Along those lines, we next examine how the modeling strategies adopted by the two main MABMs communities determined the nature of their contribution to macroeconomics.

IV. Modeling strategies and research agenda.

While the two programs have a great deal of common analytical grounding, they follow distinct modeling strategies which in fine introduce distinctive elements in their respective research agendas. It is our objective in this section to survey their actual contributions, and how they defined their

[51] Delli Gatti, Gallegati, Greenwald, Russo and Stiglitz (2006).

research agendas. We first examine the two strategies adopted by the CATS' team, and then the strategy adopted by the K&S research program.

In exploring the CATS modeling strategy, it is clear that the objective was to explore financial mechanisms and instability to enable a better explanation of the observed fluctuations[52]. This led to the development of different models exploring various microeconomic interactions involving heterogeneous agents. While the team became increasingly concerned with empirical validation, their work like early work on complexity economics is marked by a clear normative dimension. They mainly produced financial business cycles models and financial network dynamic analyses.

Financial business cycles.

Financial business cycles research was aimed at improving the capacity of business cycles models to reproduce stylized facts and observed regularities and this was the focus of the CATS research program. Its contribution centered on introducing heterogeneity in a financial accelerator model. In 2002, Gallegati and Giulioni showed that in models where firms are characterized by two sources of heterogeneity based on their balance sheets and their size, idiosyncratic shocks can generate large fluctuations. The 2005 business cycles model which was based on a scaling approach was a crucial advance. It modeled heterogenous agents' behavior explicitly in a decentralized economy. It introduced a leveraged aggregate supply in line with GS (1990, 1993) in a MABM model to examine the interactions among different financially fragile firms and the banking sector. The distribution of heterogeneity[53] proved an essential factor explaining the amplified fluctuations. The team provided further developments of and extensions to this initial model, gradually building a

[52] Delli Gatti and Gallegati were in close contacts with Hyman Minsky long before they started with ABM. They always had the objective to understand financial fragility microeconomic foundations.
[53] In this model, the authors introduce heterogeneity in firm' size and firm growth rates. The initial distribution of this heterogeneity matters and the moments of distribution by financial position vary with the business cycle.

general approach which revealed the pillars of this new macroeconomics paradigm, a project described very clearly in Delli Gatti *et al.* (2011).

Assenzia and Delli Gatti's (2015) paper was an important turning point. Their model analyzed the connection between capital and credit, and its influence at the macroeconomic level. It introduced a distinction between capital and consumption goods, and the idea of "a stylized supply chain where upstream firms (…) supply a durable and sticky input (capital) to the downstream firms, who produce consumption goods" (Assenzia and Delli Gatti 2015:5). Both types of firms are reliant on bank loans to fill their finance gap. This model combined with the tensions and frictions related to labor (and goods) markets, explains how distortions in respective financial conditions can lead to crises. Finally, Assenzia and Delli Gatti (2019) proposed a hybrid macroeconomics & agent-based model (M&ABM) which examines a (financial) market based on an ABM. This ABM generates artificial data represented by an aggregate variable which then is introduced into the macroeconomic (i.e. DSGE-type) model. Ultimately, these macroeconomic model variables have impacts at the ABM micro (individual) level which result in two feedback effects. In this model, firms' financial conditions (net worth) are heterogeneous which has direct consequences for the different external financial premiums that exist because financial frictions are considered. In this context, agents determine their optimal investment levels: when the interest rate increases the firm's profits and consequently net worth decrease. So, interest rate changes affect the distribution of firm heterogeneity. The main findings of this model are: i) that the diffusion of shocks depends on the degree of firm heterogeneity, and ii) that the distribution of firm heterogeneity is affected by the shocks. Not only does their paper show that MABM allows the emergence of the observed aggregate fluctuations; it provides a direct comparison to traditional macroeconomic models.

Credit network matters.

Superimposing a network structure on a (M)ABM is another modeling strategy. Credit relationships by their nature are complex[54]. First, they involve both heterogeneous agents and different categories of agents (banks, financial markets, pension funds, etc.). This results in different types of credit: i) inside credit which is credit between the same class of agents (e.g. inter-firm credit), and ii) outside credit which is credit between different classes of agents (e.g. households and banks). Second, the credit network is not given but is continuously evolving: some relationships are interrupted, some new relationships are forged. Third, credit networks are fragile since if one agent's net worth is sufficiently affected by a shock, its resulting financial condition will affect the financial conditions of its links (in the same or a different class). In the case of bankruptcy, there may be a domino effect such that a relatively small shock could generate huge fluctuations. An interesting finding in this literature is that although a larger variety of credit sources should diversify lender risk, the existence of large lenders involving many borrowers propagates financial distress. This idea emerged in SG (2003) and was later examined through an ABM lens by Delli Gatti *et al.* (2006) and Battiston *et al.* (2009)[55]: the size effect ("too big to fail") proposed in the face of a crisis, could be dominated by a *connection effect i.e.* the more connected the institutions/agents the more important it is to bail them out ("too connected to fail")[56]. In 2012, Battiston *et al.* employed this framework to explore the effect of risk diversification on systemic risk. They analyze default cascades in financial networks and identify two potential external effects which contribute to the ongoing discussion on the stabilizing effect (i.e. the impact or lack of it on the systemic risk) of risk diversification strategies.

[54] Delli Gatti *et al.* (2010b).
[55] Stiglitz was a co-author of most of the papers produced by the CATS' team dealing with credit network, so Delli Gatti *et al.* (2006), (2007), (2008c), (2009), (2010a) and Basttiston *et al.* (2009) and (2012).
[56] This literature has similarities to work on stress tests (Aymanns *et al.* (2018)).

The K&S strategy looks different. Although the model calibration came later, from the very first model they produced the aim was to compete directly with DSGE models, and to provide a general model i.e. to explain growth, cycles and unemployment dynamics.

Long-run dynamics and financial factors.

The K&S program pays attention to both long-run dynamics and fluctuations but considers them as the joint product of capital accumulation. Dosi and Roventini (2017) proposed a Schumpeterian growth model based on complex interacting heterogeneous agents in which demand (Keynes) and credit cycles (Minsky) elements affect short-run decisions which in turn determine long-run growth. The core of these dynamics lies in the coincidence (or not) between innovation (emergence and diffusion) and (sufficient) demand. Banks can amplify but are not the source of fluctuations. Finally, the model can reproduce persistent fluctuations and match the business-cycle properties concerning productivity, price, inflation and markups. The modularity of MABMs in general, and the strong emphasis K&S puts on the articulation between demand and supply forces, prompted many similar papers investigating economic and especially, monetary and fiscal policies[57].

V. Some preliminary conclusions

This literature provided the microeconomic foundations for the emergence of macroeconomic financial instability. Rather than introducing market frictions, it uses local interactions among heterogenous agents. Indeed, the essence of (M)ABM is the decentralized nature of the economic system[58], a framework which renews macroeconomists' interest in coordination issues. Because these models benefit from computational techniques, they are able to overcome the traditional aggregation constraint, and represent an opportunity to introduce agent heterogeneity, social interactions and bounded rationality[59].

[57] Fagiolo and Roventini (2012).
[58] Models with decentralized multi-market transactions.
[59] There are also mainstream complexity economics which means that the ACE need not reject rational expectations or equilibrium (cf. Heise 2017).

Introducing interactions adds some degree of the social dimension compared to consideration of individuals in isolation in DSGE models. Epstein (2006) clearly distinguishes between the MAB approach which refers to a social science model of the economy and standard economics based on a natural sciences model. He considers that natural science models treat the social world as a natural world i.e. with invariant laws whereas social science models can influence the laws that govern the world since they assume interactions between the development of a science and changes in behaviors based on the agents' knowledge about these developments. Thus, there is a clear ontological divide over the nature of economic agents (cf. Davis 2018). Social science models conceive economic agents as elements of a larger network. They see these economic agents as of particular relevance to the analysis of financial instability which depends not only on the agents' characteristics and decisions but also on the decisions of other agents, thus on their different distribution and on the network morphology. Because those models describe the economy as a "complex, adaptive, dynamic system", learning and expectations[60] matter and the adaptivity presumes that agents are backward-looking and learn from past events, and can extrapolate[61].

In the development of an empirical validation method, (M)ABM gradually abandoned the pure theoretical (normative) position and became more applied in order to provide alternative economic policy guidance. In addition, although initially those models suffered from the diversity of their modeling strategies and consequent unstable economic policy conclusions they have improved in this area. Currently, in both the MABM and DSGE literatures, there is (i) a clear epistemic community of MABM authors, and ii) within that community there are clear groups organized around the same core models and concentrated on specific questions, and iii) a definite (and increasing) overlap among the topics addressed and some convergence in their economic policy conclusions which is reinforcing their

[60] Leijonhufvud (1986: 4) argues that the dependence on the state of expectations is "the main reason why macroeconomists do not compare favorably with natural scientist when it comes to predictions" .
[61] Foresight is possible but over finite horizons and sequentially modified in light of realized outcomes (cf. Delli Gatti *et al.* 2008c).

credibility, and iv) greater convergence in terms of empirical validation methods[62] which is enabling more systematic comparison. Finally, DSGE modelers initially refused to investigate this approach arguing that, in the absence of any guarantee of *control*[63], they preferred *discipline* (standard microeconomic foundations); however, current MABMs enable greater control and are able to compete on that front with DSGE models[64].

It is undeniable that MABMs have passed an important theoretical and empirical milestone. We have shown that they have new microeconomic foundations for financial fragility which allow interesting economic policy conclusions[65]. Are these aspects sufficient for policy makers to consider them an alternative to DSGE models? Indeed, while today MABMs have gained reputation and have been introduced in various central banks[66], they are still not fully integrated in the policy-makers toolkit[67]. Perhaps a hybrid model[68] as proposed by Assenza and Delli Gatti (2019) might have a better chance of achieving this - at least in the short run. Whether this potentially would increase the appreciation of a "genuine" MABM is difficult to estimate.

[62] Lux *et al.* (2018).
[63] The capacity to "control" models' is understood here as the decision to stick to traditional microeconomic foundations, and this way, to stabilize the results and as well as economic policy conclusions. Still today, DSGE modelers consider that any possible alternative microeconomic foundations strategy is excluded because in addition to not easily being justified, it increases the range of possible economic policy conclusions.
[64] Chatelain and Ralf (2014).
[65] Fagiolo and Roventini (2012).
[66] Haldane and Turrell (2017).
[67] Plassard (2019).
[68] "Hybrid models" are recent attempts to incorporate insights from agent-based computational economics into DSGE models.

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