Time to rebuild and reaggregate fluctuations

Minsky, complexity and agent-based modelling

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Statement of originality:

This work contains no material which has been accepted for the award of another degree or diploma in any university, and to the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made in the text of the thesis.

For Chris.

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The titling inspiration is credited to Kydland and Prescott of the Real Business Cycle Theory, authors of *Time to Build and Aggregate Fluctuations*.

Contents

Introduction

This thesis argues for a synthesis between Minskian and complexity approaches. It compares conceptual frameworks, provides an extended example of how a synthesis can be applied, and considers the formal consequences through a systematic review of Minskian agent-based models (ABMs). Complexity insights bring forward the connection between coarse-grained macro-dynamics with fine-grained micro-specifications. In the Minskian oeuvre, this translates into linking the levels between speculative microeconomic investment decisions and recurrent economic fragility. The cyclical patterns of fragility, expressed via macroeconomic fluctuations, are not the product of exogenous shocks - aggregate cycles are constituent features of capitalist markets, that are produced by the interactions between firms, households and institutions. To put it simply, cyclical economic fragility is a complex phenomenon that requires theories and methods sensitive to complexity itself.

Complex systems thinking involves probing the ways in which patterns are generated from micro-level interactions, and how those patterns feedback into the micro-level to create continual change (Arthur, 2013: 2). A system is complex if it is cohered as a non-trivial sum of its parts, with complexity theory representing a transdisciplinary research programme that dissects *how* this non-triviality comes about. As such, complexity manifests in many ways; an evolutionary biologist studying the expression of a species phenotype and a sociologist using structuration theory are both dealing with complex systems. The framework shares roots with agent-based modelling, inspired by mathematical biology and co-developed through the computational sciences. ABMs use computational methods to simulate multi-agent interaction, testing the relationship between microspecifications and emergent macro-phenomenon. As a result, computational modelling acts as the methodological partner of complex systems thinking.

The field of complexity was birthed after the failures of chaos theory and catastrophe theory, finding itself touted as the prodigal third child of general systems theory and cybernetics. Throughout recent years, both heterodox and orthodox economists have commented that 'complexity' represents a novel path toward rectifying the troubles of contemporary macroeconomics (cf. Colander et al., 2003; Moore, 2006; Arthur, 2013; Zeidan & Richardson, 2010; Page, 2016; Battiston et al., 2016). Complexity and ABMs, as an ensemble, are described as new 'movement' capable of rectifying the extant problems of the mainstream paradigm (Arthur, 2013: 2), by turning attention toward understanding the economy as a complex system (Tesfatsion, 2002; Farmer & Foley, 2009). The complexity literature has developed along transdisciplinary lines, spearheaded by physicists, computational scientists and biologists associated with the Santa Fe Institute (cf. Gell-Mann, 1992; Axtell, 2007; Farmer, 2012; McCauley, 2009). Proponents suggest that complexity represents the shifting sands of science, 'shedding their certainties and embracing openness and procedural thinking', with both complexity and ABMs using process analysis rather than closed-form equilibrium solutions (Arthur, 2013: 19). The credibility of this claim is still up for debate,

as the dominance of positivism and deduction imbued in the tradition of the physical sciences forces a spurious flattening of social reality and its partial its partial expressions, i.e. empirics. There is overwhelming reliance on 'letting the data speak', which not only imbues scientific faith in what will always be noisy, incomplete economic data, but also mutes the significance of economic theory (Moore, 2006: Ch4).

This thesis responds to the positivist overtones of the dominant approaches to complexity (i.e., econophysics) by bringing together the work of Hyman P. Minsky and complexity economics. It explores how critical discourse can inform the theoretical foundations of complex systems thinking. There are many modalities of complexity, and a synthetic framework can winnow out the appropriate tools to employ in studying economic phenomena. The Minskian complexity synthesis presents a step forward in building a complex understanding of capitalist processes, retaining the prognosis that crises cannot be 'solved' through equilibrium solutions, while exploring how emergent fragility works across the micro-, meso- and macroeconomic levels of analysis. Consequently, the assessment of contemporary Minskian ABMs are guided by how well computational modelling captures the 'vision' of Minsky, along with their pedagogical and experimental capabilities in representing a complex system.

The motivation for this stems from the fact that complexity and ABMs must climb the theoretical mountain of endogenous fragility and crises, which rises much further than merely presenting an alternative methodology to track the evolution of business cycles. Regarding the failure to foresee the Financial Crisis of 2007-09, the 'dissenting mainstream' point to wilful ignorance (Romer, 2016), unrealistic microfoundations (Pesaran & Smith, 2011), inherent stability through linearisation (Caiani et al., 2016), and the inability for dynamic stochastic general equilibrium (DSGE) models to manage endogenous cycles (Solow, 2010; Stiglitz, 2011). These are not only problems of method. They are the encumbered result of a simple ontology, with the bounds of the theoretical space defined by axiomatic general equilibrium. However, it remains unclear whether complexity and computational modelling can provide lone alternatives due to immense heterogeneity in research agendas, differing methodologies, and most importantly, a lack of clear theory.

Bringing Minskian theory into dialogue with complexity and agent-based methods therefore serves several purposes. The synthesis highlights the congruency between complex systems analysis and existing heterodox theories, making rich and robust links between ontology, theory and methodology. It also resolves some problems associated with each approach. In this thesis, the outstanding issue of Minsky's work is noted to be the fallacy of composition. Linear programming and the representative agent are used in Minsky's two-price theory of investment, which forms the basis for his 'financial instability hypothesis'. The fallacy can be resolved though complexity, using network theory and rule-based analysis to explore the mesoeconomic space between Minskian microfoundations and his macroeconomics. Conversely, using Minsky's ideas as a theoretical anchor avoids turning

complexity into a series of 'weasel words', and diminishes the primacy given to positivism by placing the tools of complexity in a broader narrative. This lens can be employed to assess contemporary ABMs, of which play a pedagogical role in exploring the processual development of economic fragility. The primary problem of computational simulation models is an underdeveloped ontology, with vague or unspecified assumptions being made about social reality. As a result, some ABMs have devolved into stylised DSGE models (e.g., Di Guilmi et al., 2015). The present thesis does not provide a final resolution to these problems, and it is an open question to how ontological complexity and model parsimony can be rectified. However, some points of consideration are highlighted by a Minskian complexity theoretic approach, such as the need to retain nonergodicity and therefore Keynesian uncertainty in an agent-based framework.

There are few, if any, similarly extensive treatments of a Minskian complexity theory, and so the current project is orientated toward opening doors to dialogue rather than absolute resolutions. Note that this thesis does not delve into policy implications nor the role of institutional governance. 'Big government' is an important aspect of Minskian theory (see Minsky, 1986/2008), but will not be discussed within this thesis due to the limited scope of the project, and for the sake of brevity. Rather, the current project is exploratory and theoretical; that is, it traces the theoretical implications of a synthesis and uses complex systems thinking to build on understanding the drivers of economic fragility.

The thesis does, however, stand on the shoulders of several Post Keynesian theorists who call for the absorption of complex systems thinking into Post Keynesian Economics (PKE). Basil Moore (2006) argues that complexity provides a cohesive base for conceptions of uncertainty and system nonergodicity, turning the heterodox project from convincing the 'academy' that an idea or axiom is valid, to one pushing for a recognition that the economy is a complex system. Rosser Jr (2006: 22-23) argues that complexity theory provides an ontological and technical through line between the disparate schools of PKE, with the deepest link being the conception of endogenous aggregate fluctuations. The complexity literature shares nonequilibrium and reswitching dynamics with the Sraffians, nonlinearities with the Kaleckians, and nonergodicity for the fundamentalists i.e. Davidsonian and Minskian strands (Rosser Jr, 2006, 2010, 2013). Velupillai (2013) suggests the technical insights of complexity (i.e., nonlinearity, nonmaximum dynamics, and computational modelling) must be added to the Post Keynesian toolkit to expand the formal robustness of theories around aggregate fluctuations. Indeed, complexity research into endogenous volatility (e.g., Gomes, 2014), nonlinear and 'irregular' dynamics (e.g., Day, 1992, 2000) are congruent with Minskian theories of cyclical fluctuations, and both share a rejection of the general equilibrium framework (cf. Minsky, 1993a, 1986/2008; Lux & Alfarano, 2016; Farmer, 2012). It is then no surprise that recent Minskian agent-based models absorb complex systems thinking through evolutionary adaptation, non-equilibrium analysis, and networking theory. The most direct example is the Minskian agent based-stock flow consistent models of

Seppecher & Salle (2015) and Seppecher et al. (2016), which can simulate sentiment-driven endogenous cycles and their impact on multiple sectors of the economy.

Nevertheless, there are some extant issues to be ironed out. What is discarded and adopted in a Minskian complexity synthesis? What are the specific micro-, meso- and macroeconomic dynamics that underpin this approach to endogenous cycles? What exactly replaces equilibrium analysis? Are there any implications for existing ABMs if a complex ontology is adopted? The current project probes these questions through three distinct paths divided into chapters, converging as an extended example of one way heterodox and complexity theories can meaningfully interrogate one another.

Chapter One is an introduction to Minskian and complexity approaches to aggregate fluctuations, outlining the congruent and incommensurable ideas present in each. The justification and defence of the proposed synthesis stems from the fact that complexity applications can successfully retain the underlying vision of Minsky, while adding analytical depth. The types of complexity are discussed relative to the Minskian framework, namely 'restricted' and 'general' complexity with respectively refer to system analysis and ontology-epistemology. Outstanding critiques for both complexity and Minskian approaches are outlined, with some answers via a synthesis developed in the following chapter.

Chapter Two discusses the micro-meso-macro dynamics of endogenous fluctuations and volatility under a Minskian complexity theory, forming the technical argument of this thesis. Here, nonergodicity and Keynesian uncertainty underpin the formation of agent heuristics, forming the 'microfoundations' of the proposed dynamics. At the meso-level, these decision rules are socially transmitted through a systems architecture, pointing to the role of market topology in the transmission of speculative behaviour. It is at this analytical level that dynamics can become paradoxical - rational microeconomic behaviour can aggregate into collective irrationality (Al-Suwailem, 2014: 393). As an idea borrowed from the evolutionary complexity approach of Holling (1973), the 'resilience-stability trade-off' is discussed to conceptualise behavioural homogeneity (i.e., herding) as fragility creating.

Chapter Three is a critical investigation of contemporary Minskian ABMs. Although presenting a formal model is out of the scope of this paper, Minskian models are presented and assessed relative to the ideas presented in previous chapters. One outstanding problem of ABMs relates to the calibration methods used, which can be problematic due to the high dimensionality of computational macro-models. Procedures to resolve this issue is a point of theoretical divergence, with some Minskian ABMs turning into a stylised DSGE model via the use of representative agents (e.g., Chiarella & Di Guilmi, 2011). This chapter argues that the representative agent framework must be discarded entirely if a complexity lens is employed, and analyses models that successfully do so (e.g., Seppecher & Salle, 2015; Seppecher et al., 2016). To conclude, a sketch of the problems associated with ABMs are illustrated, leading to a call for increased consideration about the system assumptions employed in model design.

Chapter 1

A primer and comparison of Minsky and complexity

This chapter serves as a primer to Minskian and complexity theories, from the standpoint that they are complementary frameworks. The central through-line is to present the opportunity for synthesis through a comparison of theory, methodology and epistemology. Minsky's theory of financial fragility is a cohesive diagnosis of crises in an investment-centric capitalism, using both narrative and formal reasoning to identify *why* capitalism is marred by persistent breakdowns. Although complexity approaches are highly varied, some discursive branches are traced, moving from technical ('restricted') to philosophical applications of complex systems thinking. In effect, restricted complexity dealing with evolutionary and dynamical systems analysis asks *how* crises unfold, which must be connected with Minsky's '*why*'. The call for a synthesis, however, must traverse the problem of choosing what elements are to be discarded and highlighted in the respective frameworks. Any resolution is necessarily tentative, as the literature is embryonic, but a preservation of an evolutionary and transformative ontology is crucial. This chapter outlines some points of consideration carried through the rest of this project interaction to replace the representative agent, induction over deduction, and process analysis to usurp equilibrium analysis.

Section 1.1 provides an exploration of Minsky's central thesis, the financial instability hypothesis, to illustrate the ideas to be preserved and extended through a Minskian complexity theory. Outstanding critiques of Minsky's oeuvre are presented, raising questions about the role of sentiment in speculative investment, an idea expanded upon in Chapter 2. Section 1.2 introduces relevant concepts from the complexity literature, outlining technical contributions associated with econobiology and econophysics in understanding endogenous fluctuations. 'General' complexity is also presented as a poststructuralist approach to social science, highlighting the role of ontology in research. It is posed as a friendly competitor to the critical realism of Post Keynesian economics (PKE), setting the stage for a discussion on synthesis in section 1.3. Here, the concluding argument is one that states sensitivity to the economy as a complex system must be central to the project of heterodox economics.

1.1 The Minskian vision

In discussing a paper on stock market volatility, Minsky (in Friedman et al., 1989: 174-175) notes that he seeks to explain the cyclical fluctuations observed by Joseph Schumpeter, Milton Friedman, Anna Schwartz, and Moses Abramovitz. Such explanation is provided by the financial instability hypothesis, self-described as a 'deviant interpretation of Keynes's

General Theory' (Minsky, in Friedman et al., 1989: 175).

The fundamental vision inscribed in the hypothesis is one of inherent evolutionary instability; the survival of an economic actor is dependent on the speculative accumulation of capital and profits, inducing debt-financed investment today, for uncertain returns tomorrow. Minsky adopts the methodological individualism of Josef Schumpeter to explore human agency and its relation to the future. Unlike Schumpeter (1942) who relegates the agent of change to the creative entrepreneur Minsky turns toward the firm as a force of cyclical instability. Firms negotiate with equally agential institutions, such as profit-seeking banks, to establish the terms of the agreement in debt contracts. In the words of Kuznets (1940: 259), investment is the *sui generis* function of the business enterprise, seeding fragility via increasing debt during buoyant macroeconomic conditions, eventually blooming into a deleveraging crisis.

The progression of this process is by no means short, potentially spanning decades. Palley (2011) notes that Minsky analyses both medium term (basic) cycles of approximately one decade in financial fluctuations, and a long-wave (super) cycle akin to the forty to sixty years[1]. Financial crisis and depression are most associated with super-cycles, which are a cumulation of basic-cycles that gradually erode the system.

The decomposition of aggregate fluctuations into super- and basic-cycles is not immediately apparent in Minsky's work, reflecting his tendency to commingle analytical levels. He combines both a medium-term analysis akin to the Neoclassical synthesis and the 'long cycle thinking' of Schumpeter and Kondratieff (Palley, 2011: 2). However, making a distinction between these two styles of approaching analysis requires 'reading between the lines' (ibid. 2). This ambiguity is also present in Minsky's treatment of micro- and macroeconomics.

Although discussed in more detail in later sections of this chapter, it is useful to note that the imprecise treatment of analytical levels has led some to critique Minsky as propagating a fallacy of composition (e.g., Lavoie & Seccareccia, 2001). The mechanistic particulars of Minsky's (1986/2008) financial instability hypothesis, namely the two-price theory of investment, reduces investment strategies to a negotiation between borrower and lender, which aggregates outward and misses a fundamental meso-level of interaction between agents. The subjective view of time is illustrated through a compressed analysis of one firm, leaving intra-firm interaction to an assumed or implicit process. Complexity approaches, such as that of Moore (2006) and Cilliers (1998), avoid the fallacy by *decentering* the economic agent as representative of the collective. From this perspective, the investment decisions of individuals only cohere to create patterns in the aggregate through multiple networks of interaction. To make sense of this approach and its methodological consequences, Minskian and complexity theories must be briefly introduced.

[1]Long-waves are often described as 'Kondratieff' cycles, and were analysed by Schumpeter. See Kondratieff & Stolper (1935) and Kuznets (1940).

1.1.1 The two-price theory of investment and the financial instability hypothesis

Underscoring Minsky's approach is the acceptance that excess volatility and economic crises are irresolvable problems endemic to capitalism. The traverse to some supposed 'steady-state' holds within it the forces of its undoing, with any tranquil moment being just that a fleeting moment (Minsky, 1976: 54). Any stabilisation policies that address the symptoms of a fragile system can, in fact, create an unforeseen trajectory toward the fragility it meant to diminish.

It is this vision that Minsky (1986/2008: 194) draws upon to put forward two fundamental postulates of the financial instability hypothesis:

1. There cannot be a constant stable price full-employment equilibrium under capitalist markets;

2. The mechanisms necessary for modern capitalist economies are the cause of recurrent, protracted business cycles and crises.

These statements are reflective of Minsky's vision of the economy as one of perpetual internal flux. The foundation of the hypothesis stems from this vision; a sophisticated financial system influences the macroeconomy via interconnected balance sheet relations, driven by a collective interest in profit accumulation. Rather than beginning with a profit maximisation specification of a principle-agent problem, Minsky adopts what Toporowski (2016: 96) denotes the 'stock-flow problématique': agents speculate on the income flows required to secure their stock of capital assets, which necessarily corresponds to the stocks and flows of interrelated balance sheets over time (Minsky, 1992: 3-4). Balance sheets are more than a static statement of assets and liabilities they connect past cash-flows, present decisions, and expectations of the future.

Expectations are forecasts of an uncertain future, and holding money is a form of insurance against future contingencies. This characteristic of money is described by Minsky (1986/2008: 204) as 'the virtue of liquidity', drawing from the liquidity preference of Keynes. Money non-neutrality is the general case, as intertemporal investment and consumption decisions are defined through the subjective expectations of a fundamentally uncertain future. As balance sheet relations connect time periods through financial obligations, the classical dichotomy between real and nominal variables becomes of secondary importance. Minsky (1993a: 6) argues that this division is one of analytical convenience, noting 'there is no so called real economy whose behaviour can be studied by abstracting from financial considerations'. Indeed, this is a hint that categorical reduction should not be used in studying such a 'complex evolving beast' as the macroeconomy (Minsky, 1957: 3).

The emergent fragility of the system is dependent on the capital and liability structures of firms, grounded in the two-price theory of investment (Minsky, 1986/2008: 213-218).

Here, Minsky evokes the representative firm to illustrate the role of risk perception in determining the level of external financing, represented in Figure 1.1. The two prices are (i) price of current output (P_I), calculated as cost plus markup, and; (ii) the price of capital assets (P_K), found through the intersection between asset supply and demand (Minsky, 1986/2008: 200). Capital asset supply is fixed in the short-run, with demand influenced by present value calculation of the assets future cash-flows and their liquidity. Similarly, financial asset i.e. equity, price is determined by expected cash-flow, but without the liquidity consideration.

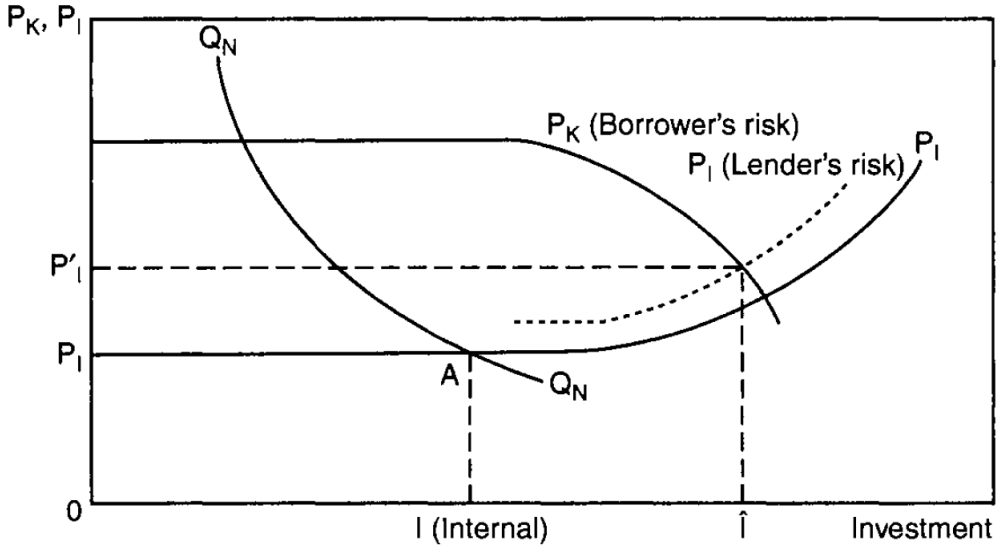


Figure 1.1: The determinants of internal finance (I) and external finance ($\hat{I}$) according to the two-price theory of investment (Minsky, 1986/2008: 213).

These prices enter into the firms net worth, by determining the total monetary and capital assets available after liability costs have been taken into account. The sum of monetary assets, e.g. profits and corporate bonds is captured in a firms internal cash-flow (Q_N), and determines level of internal financing used in investment (point A). Beyond this level, external financing is the result of a negotiation between the borrowing firm and the profit-seeking lender. The agreeable price of external financing (P_I') is found via the intersection between the borrower (P_K function) and lender's cost of risk (P_I function), respectively denoted the demand price and supply price of investment (Minsky, 1986/2008: 214). Bank risk is reflected in terms of the loan, the interest rate and credit amount, or the risk premium of a financial asset in the case of a public offering. As such, lenders are characterised as active, profit-seeking actors, rather than passive facilitators.

Minsky largely overlooks the social and psychological aspects of speculative sentiment of Keynes's (1936) 'animal spirits', but the two-price theory, when aggregated outward, implies that *collective* bias in risk assessment can create increasing financial fragility. Buoyant

macroeconomic conditions, characterised by strong aggregate demand, suppress perceived risk and uncertainty, reducing the virtue of liquidity. If speculation over expected profits drives an increase in investment under this accommodative environment, there may be an evolution towards generalised fragility, as more firms take on increased absolute debt. A small increase in commercial interest rates may impact the terms of repayment of contractually obliged firms, suggesting the nonlinear nature of an endogenous disequilibrium sequence in a fragile economy. Unfortunately, the interaction between firms is mostly absent from analysis, negating the influence of contagion-like spread of optimistic or pessimistic behaviour in the degree to which investment is undertaken. Minsky (1986/2008: 49) does briefly comment on the role of 'socialisation' in speculative risk-taking behaviour, although for the most part, the agent is framed as *introspective*, looking inward to balance sheet calculations and only outward to macroeconomic fundamentals.

Minsky introduces a tripartite heterogeneous agent schema to trace the evolution of economic robustness to fragility. The efficacy for external finance to be destabilising is dependent on the financial position of firms, namely their ability to repay the principal and interest on outstanding debts. Minsky (1992: 6) categorises firms into hedge, speculative, and Ponzi firms according to this ability. If hedge financiers denominate the financial system, the majority of firms can repay both principal and interest on the outstanding debt by drawing on cash flows. The transition toward a fragile system is marked by the rising rate of speculative financiers, who can fund the required interest repayments, but cannot meet the principal of the loan. Hedge firms become speculative by expanding externally financed investment under the expectation that future cash flows will continue to rise.

Consequently, increases in commercial interest rates or a reactionary monetary policy tightening may reduce the ability to service interest repayments, turning firms into Ponzi financiers. Fragility is rife when Ponzi financiers dominate the market, meaning most firms cannot fulfil any of their contractual repayments and must deleverage their position to meet the required repayment. Minsky (1992: 8) hypothesised that a Ponzi economy would lead to Fisherian debt deflation due to panic selling, as firms collectively deleverage their position to avoid bankruptcy.

1.1.2 Outstanding critiques and a sketch of possible resolutions

The picture created by the financial instability hypothesis is one where firms, differentiated by balance sheet composition, interact with the world through an interpretation of the state of the macroeconomy, banks and governmental institutions. Banks have agential power by way of a profit motive, naturalised as a component of their function as risk-assessing lenders. Much like business enterprises, the risk perception of banks is a product of inferring insights from macroeconomic fundamentals. However, Minsky's treatment of evolutionary financial fragility raises some questions about the conceptualisation of economic actors, and in particular, how the decision of an individual relates to that of the collective.

A highly discussed logical inconsistency that echoes this question the is the *paradox of debt* (e.g., Lavoie & Seccareccia, 2001; Bellofiore & Halevi, 2011). The paradox was originally noted by Steindl (1952), and describes the situation wherein economic agents, by attempting to decrease debt and leverage ratios, collectively increase aggregate indebtedness by reducing investment and therefore aggregate demand. Turning the paradox around, an increase in individual debt translates to a total decrease in debt by stimulating aggregate demand. By taking on external finance, firms boost income and consumption through an increase in investment, resulting in strong cash flows that can service the outstanding debt. As a result, the Minskian outcome wherein extending external finance can create aggregate indebtedness, is nullified.

The cause of this logical inconsistency in the Minskian thesis is sourced by Lavoie & Seccareccia (2001: 85) to the representative agent. This methodological misstep creates a fallacy of composition, with the paradox highlighting the fact there is no reason for leverage ratios to be procyclical as per Minsky's theory. Although the procyclicality of leverage has been empirically validated (see Adrian & Shin, 2013), attempting to resolve this paradox points to the somewhat unclear treatment of speculation and uncertainty.

To illustrate this and motivate the entrance of complexity, consider the following. Debt contracts are burdens carried across irreversible time. If it assumed that credit creation is a precondition for bank deposits and debt is fixed in nominal terms, this increase in debt pushes inflation upward by an expansion in bank balance sheets. External debts decline in real value, feeding back into to the accumulation of additional liabilities. However, if firms only calculated decisions according to their current cash-flows, there is no reason to undertake external financing beyond the current level of demand. It is the *speculative assumption* that demand will grow that raises indebtedness to precarious levels, opening the system up to fragility due to the time it takes to validate, potentially long, amortization schedules. Wages may remain stagnant as a result of cost-minimisation on the part of the firm, or even decline with higher inflation, creating insufficient aggregate demand as indebtedness increases. So, what drives such mass speculation required to create macroeconomic fragility?

Minsky argues,

> Financing is often based upon an assumption "that the existing state of affairs will continue indefinitely" (Keynes, 1936: 152), but of course this assumption proves false. During a boom the existing state is the boom with its accompanying capital gains and asset revaluations. During both a debt-deflation and a stagnant recession the same conventional assumption of the present always ruling is made; the guiding wisdom is that debts are to be avoided, for debts lead to disaster. As a recovery approaches full employment the current generation of economic soothsayers will proclaim that the business cycle has been banished from the land and a new era of permanent prosperity has been inaugurated. (Minsky,

1976: 126).

One critique may be that 'the existing state' for firms can either be hedge-like or Ponzi-like, normalising to zero in the aggregate. However, it is implied that there is some *social transmission* of expectations by the 'soothsayers' who normalise a state of sentiment. This idea is undeveloped in Minsky's instability hypothesis. '[W]hirlwinds of optimism and pessimism' are simply assumed to influence the movement of speculative markets and reinforce overinvestment (Papadimitrou and Wray, in Minsky, 1986/2008: xii). In a later work, Minsky (1996: 359-364) does briefly discuss the role heuristic rules as guiding the investment decisions of boundedly rational firms, but there is a significant threat to relegating the role of expectational bias to an assumed, ambiguous process. As Velupillai (2013) notes,

> The transition from [hedge, speculative and Ponzi] is when "Keynesian uncertainty" kicks into action, although it is not clear, in Minsky's voluminous writings - nor in any of those by Minsky scholars - how this is played out by the interaction. (Velupillai, 2013: 427)

The scope for some clarifications come via complexity approaches to sentiment-driven endogenous cycles, further addressed in Chapter 2 and 3. One point of note is the framing of analytical levels in complex systems thinking. The 'gap' between individual rationality and the aggregate collective is the *meso-level* of interest (Al-Suwailem, 2014: 393); the mesoeconomy is the space of which normalisation of speculative finance occurs. Broadly categorised as the localised networks of interaction between agents, the meso-level supports over-optimistic investment through the socially transmitting speculation, legitimising sentiment the 'animal spirits'. Expectational bias and the accumulation of debt can be stimulated and validated by network connections between firms and financial institutions. The economy can become 'locked-in' toward a path of fragility, with commercial and central banks facing increasing risk, stifling the ability for prudential tools or interest rate controls to reduce risk without forcing mass deleveraging and bankruptcies.

1.2 A primer on complexity theory

In taking a momentary step back from these micro-technical details, Minsky's perspective, his pre-analytic vision, is outlined as evolutionary and dynamic. The question probed in his oeuvre is one foundational to the social sciences: 'How to we connect the behaviour of an individual to the structure which they exist?' To Minsky, this connection is primarily defined through microfounded balance sheet relations which both express, and are expressions of, an investment-driven financial capitalism. The complexity perspective is concerned with much of the same; in particular, complexity asks *how* a system is cohered as a non-trivial sum of its parts, whether that be in terms of historical evolution, multidimensional

networks, system movement or epistemic understanding itself (c.f. Simon, 1962; Holland, 1992b; Cilliers, 1998).

Restricted and *general* complexity, first noted by Morin (2007), are used here to roughly equivalent to system theories and ontology, respectively. Restricted complexity is 'restricted', because it sets the epistemic bounds of which theory-building occurs, '[acknowledging] the non-linear, relational nature of complex systems, but [seeking] to tame it in ways which reintroduces positivism and reductionism' (Cilliers, 2010b: 41). It is further decomposed into *aggregate* and *dynamical* complexity following the typologies of Manson (2001) and Rosser Jr (2004), to distinguish between the broadly biological and physical methods employed. General complexity is an ontological and epistemological project that stresses the fundamental limits to knowledge in a truly intractable reality (Preiser & Cilliers, 2010). Under this perspective, the external world is continually changing, and so knowledge of it is always an incomplete local narrative. Consequently, dualisms associated with the scientific method are relaxed, e.g., objectivity/subjectivity, real/abstract, holism/atomism (Preiser & Cilliers, 2010: 268-269).

1.2.1 Restricted complexity

Aggregate complexity

Aggregate complexity is a systems theory of interaction, that suggests the relationship between units produce aggregate coherence by way of emergent patterns, such as economic crises. System coherence is not necessarily stable or uniform, with no direct universal control that governs functionality. Consider the following features of an aggregately complex system put forward by Cilliers (1998: 8-9):

1. There are many heterogeneous agents who interact, adapt and learn;
2. Spatial and informational constraints bound interaction, e.g., bounded rationality;
3. Information is spread across many agents simultaneously;
4. There are positive and negative feedback loops; and,
5. It is an open system that is regularly out of equilibrium, with unclear division between exogenous and endogenous variables.

Many of these features are also present within Minsky's financial instability hypothesis. For example, firms are heterogeneous in liability structures, differentiated into hedge, speculative and Ponzi financiers. They do not have rational expectations nor perfect information, with fundamental uncertainty and risk proper acting as spectres haunting investment. Additionally, the economy never settles into a fixed-point Walrasian equilibrium to

any meaningful degree; in fact, the hypothesis is a direct response to the self-equilibrating tendency espoused in the neoclassical synthesis (Minsky, 1986/2008: 196-199). Minsky does miss some key points however, namely that of social interaction, learning and the movement of information across networks.

Applications of aggregate complexity in the study of financial crises, borrow tools from networking theory and mathematical biology to explore the conditions and results of economic crises, often through agent-based modelling (see e.g., Kolb, 2011), further discussed in Chapter 3. Ideas of biological evolution play a fundamental role in explaining the internal changes of the economy, spawning the subdiscipline of *econobiology*. Econobiological perspectives, such as that of Arthur (1995), frame evolution in markets as one of cognitive change and learning, with crises representing a culmination of contingent adaptations that conflict with the broader environment (see also, Zeidan & Richardson, 2010).

Complexity is most potently illustrated by the fact that these individual adaptations are highly heterogeneous, meaning agent level adaptation does not necessarily aggregate outward to system-wide adaptability as is usually assumed (Wilson, 2014: 31-32). Complex systems with many hierarchically organised subsystems may have conflicting responses to environmental change, leading to an ambiguous or counterintuitive aggregate response. An example of this is *the paradox of risk*, which describes the tendency for systemic risk in the financial system to increase when individuals collectively attempt to reduce risk through diversification. The paradox of debt as presented by Steindl (1952) is also an example of a micro-macro conflict where adaptive microeconomic responses are collectively maladaptive. If adaptations are even across analytical levels, i.e. micro-macro, then secular evolutionary changes would follow systematic convergence to a stable optimum, as no internal conflict occurs. By use of the representative agent, Minsky leaves ambiguous the processes of evolutionary change that work across analytical levels. Recall an earlier point: if firms are heterogeneous, facing different degrees of profits and losses, there is no *a priori* reason for firms to suddenly increase debt financing under the assumption that 'the existing state continues indefinitely', because the existing state may be different for every firm (Keynes, 1936: 152).

Dynamical complexity

Dynamical complexity is concerned with understanding the often irregular movements and statistical properties of economic systems, using the tools from dynamical physics to analyse complex systems. Although Rosser Jr (1999: 170-171) argues that the dynamical framework captures within it the aggregate biological perspective outlined above, the epistemological orientation is fundamentally different. In dynamical approaches, the research questions often pertain to whether empirically observed patterns follow an underlying universal law, or whether it is reducible to some equation(s). As a result, theory and social philosophy often escapes dynamical discourse (cf. Rosser Jr, 2008).

Nevertheless, many facets of the Minskian hypothesis are captured via dynamical systems analysis. Generally speaking, a system is dynamically complex if:

1. **Macrodynamics are nonlinear.** Nonlinearity is observed when variables have an output proportionally unequal to their input, such as in the case of a commercial interest rate change causing mass bankruptcies in a fragile economy. At a systems level, nonlinearity is also observed through sensitive dependence to initial conditions (SDIC). If a system exhibits SDIC, infinitesimally small changes in the original specifications of the system can create extreme divergence in the long-run, compared to if the change did not occur. SDIC reflects path-dependency, non-forecastability, and Keynesian non-probabilistic uncertainty: no *a priori* calculation of path probabilities can accurately forecast the long-run movement of a complex system unless all the value of all variables, their behaviour, and the exit and entry patterns are known exactly.

2. **There is no fixed point equilibrium.** This non-equilibrium characteristic refers to system aperiodicity, wherein no stable long-run equilibrium is derivable through a Brouwer fixed-point theorem (as is used in the general equilibrium theory by Arrow & Debreu (1954)). It also means there are no aggregate cycles that precisely return to in its initial state, as minor perturbations accumulate across time, a point shared by the Minskian hypothesis. A fixed point equilibrium can only occur if the system or its parameters are constant and non-dynamic.

3. **The internal rules of a system change.** Endogenous phase switching occurs when the system equations change in different state spaces or over time (Day, 1992: S9). For example, Sethi (1996) analyses *endogenous regime switching* as the way in which investment strategies change according to market conditions, of which are products of the strategies themselves. Under the instability hypothesis, endogenous rule changes are also seen in the feedback processes between the macroeconomy and speculative investment, changing across different phases of aggregate cycles.

Dynamical complexity is most associated with econophysics, using the methods of statistical physics, quantum theory and fluid mechanics to untangle the behaviour of complex systems. The problem with the econophysics literature is that while it is empirically robust and offers novel methodologies, there are often no theoretical foundations for much of the research. Primacy is given to robust empirics over any theoretical narrative, with econophysics being described as 'data analysis first and hypothesis formulation second' (Zeidan & Richardson, 2010: 3).

Econophysicists like McCauley (2006, 2009) believe they are subverting mainstream thought, with radically *new* insights into market processes. McCauley (2009: 201, 204)

finds that the subjective value of asset prices imbued in speculative markets lead to endogenous fragility, and argues that long-run equilibrium solutions are irrelevant. These are ideas commonly associated with Minsky and Sraffa, and even a brief foray into heterodox economics would have revealed this to be the case. Yet, McCauley (2006: 607) argues, '[n]o existing economic model or idea provides us with a zeroth order starting point for understanding how real markets function.'

This is not to downplay the insights provided by dynamical approaches. There have been attempts to formalise Minsky's financial instability hypothesis using methods found in physics (e.g., Assenza et al., 2010; Delli Gatti, 2012), as his theories are not easily translatable into standard economics and econometrics:

> The nice equilibrium solution that economists have been trained to seek does not exist. The modelling leads to complex non-linear time-dependent relations which, as attempts to model and solve or simulate these ideas has shown, lead to complex time series which exhibit what can be considered periods of chaotic behaviour. (Minsky, 1993b: 34)

Much of the research in econophysics supports the Minskian hypothesis. The endogeneity of cycles is traced to the composition of speculative behaviour in financial markets (Zeeman, 1977; Cobb, 1980; Rheinlaender & Steinkamp, 2004), mirroring the hedge-speculative-Ponzi schema of Minsky. Furthermore, there have been successes in accepting the persistence of excess volatility and crises in the dynamical literature. A famous example of this comes from the father of econophysics, Benoit Mandelbrot (1963) who found that asset returns were not normally (Gaussian) distributed, and instead were characterised by 'fat-tails' that suggest the regularity of financial instability. The assumption of normality was employed since Bachelier (1900), and can be seen in Modern Portfolio Theory (Markowitz, 1952) and early versions of the Capital Asset Pricing Model (Sharpe, 1964). These insights into stylised facts have also been subsumed into mainstream discourse, for example via contemporary versions of the Black-Scholes model, which appears odd considering the supposed rejection of mainstream economics within econophysics. The reason for this is simple, however: it is because there is no theory behind the tools, and without theory, these insights become descriptions.

1.2.2 General complexity

Contrary to econophysics, general complexity is a philosophical position that supposes the impossibility of permanent universal knowledge, an approach primarily developed by Cilliers (1998, 2005) through a lens tinted with poststructuralist colours. A useful entry point is to compare this approach to the critical realism of Lawson (1999, 2006), who argued that PKE and heterodox economics more generally, must be poised on an ontology of open-systems. Dow (2002: 173) points out that critical realism closely aligns to the logic of

Keynes (1921), devoted to understanding *objective* causal processes without imputing the necessity of establishing causal laws. As such, a critical realist ontology supposes a social reality in continual flux, with 'relational emergence' that cannot be reduced into axiomatic formations (Elder-Vass, 2010: 67).

General complexity and critical realism are ontologically similar, both rejecting the pretence put forward by the mainstream that social reality is compressible into a series of functions. Indeed, this implicates restricted complexity insofar as the econophysics paradigm attempts to re-inject positivism into the study of complex systems, with criticisms from Horgan (2004) arguing that complexity approaches aim to find 'truths' under an ontology that refutes the possibility of 'truth' at all.

It thus follows there are two questions to answer, 'does general complexity offer anything different to critical realism?' and, 'can the theories of restricted complexity be rectified with the general?'. The answer to both is 'yes', and for the same reason: general complexity posits the inseparability of the observer and the observed. The epistemological consequence is one that accepts that any identified causal process is a partial representation of the world, whether it by via narrative reasoning or formal logic. Social reality is so complex that it can never be understood through absolute holism, as any analysis is motivated by the normative and ethical principles of the observer. Theory is performative, and knowledge does not exist in an objective/subjective dualism. It is an expression of a 'local narrative' which cannot be measured in truth value when compared with an external social reality that is necessarily cohered experientially (Moore, 2006: 69).

This is not to say complex systems are purely stochastic or unstructured. Following the arguments of Cilliers (2010a: 8) and Dow (2004), for a system to be operational, it must have structure, even if there is some constant change. Similarly, any theory addressing a system must be closed, by placing boundaries on what is analysed and ignored. Social reality may be open, but attempting to approach it as such is impossible.

General complexity posits sensitivity toward the difference between theory and ontology while empowering the normative dimension, a point often unaddressed by positivist extensions of restricted complexity. Critical realism gives primacy to uncovering the processes of an objective and complex reality - but as Kaul (2002: 714) notes, this requires that some theories, or representations of the world, be more 'real' than others, even if such property is transient. General complexity on the other hand, does not necessarily reject that there exists an external world but rather shifts the focus toward how understanding (a 'complex epistemology') co-produces ontology (Preiser & Cilliers, 2010: 267) via a social philosophy. Returning to the Minskian hypothesis makes this point clear. One interpretation, the critical realist position, may be that the financial instability hypothesis is a theory of processes that usurps the mainstream conception of cyclical fluctuations as exogenously triggered, by presenting a theory that is more aligned to social reality. This is how Minsky (1986/2008) himself partially justifies the financial instability hypothesis, as one orthogonal

to the neoclassical synthesis, adopting dialectical historical time and uncertainty as ontological precepts. It is not, however, an exploratory foray to find the *true* 'causal mechanisms and generative structures' as is required by critical realism (Austen & Jefferson, 2006: 259).

Instead, general complexity suggests it is the framing of reality that matters. Ideology and ontology co-produce one another, shaping the questions asked and the methods of approaching the problems. Minsky provides a critical diagnosis of capitalism, a political and ethical position for reform, inseparable from the analysis itself:

> Although [*Stabilizing an Unstable Economy*] is mainly concerned with economic theory and some interpretive economic history, its aim is to draw up an agenda for the reform of our malfunctioning economy. Effective reforms must be consistent with the processes of the economy and not violate the character of the people. Without an understanding of the economic process, and without a passionate, even irrational commitment to democratic ideals, an agenda for change, in response to a perceived need for change, can become the instrument of demagogues who play on fears and frustrations and offer panaceas and empty slogans. (Minsky, 1986/2008: 10).

In sum, the ontology of general complexity and critical realism are very similar, focusing on open-systems, emergence and dynamical movement. The point of difference is meta-methodological; that is, there is increased sensitivity to the inherent incompleteness of knowledge in attempting to understand a complex system[2]. As such, the ontological and theoretical distinction must remain clear. Formal representations, which are necessarily simplified snapshots of complexity, should not be presented as *the* reality, but merely attempts to approach *a* reality in a particular way.

1.3 On the purpose of a synthesis

The elements of a synthesis have been outlined, albeit in a manner that is scattered and multidirectional. The Minskian hypothesis presents a theory of financial capitalism that digs into the mechanistic particulars, aligning with the ontology of a complex, evolutionary system. The fallacy of composition is addressed by aggregate complexity, with dynamical approaches providing a positivist extension of Minsky's theory. Underscoring this is general complexity, a philosophical framework that highlights pluralism and ethics in broaching the problem of systemic crises.

Before embarking on an applied synthesis in Chapter 2, some questions must be briefly addressed. The core issues that any synthesis must tackle relates to how and why a synthesis is a meaningful intervention. What are the merits? Are there criteria for achieving a

[2] A rejoinder to this may be that general complexity is liable to relativism. It is not addressed here, but Moore (2006) and Cilliers (2010a) provide a response.

successful synthesis? These questions will find no final answer here, but the guiding pretence for the following chapters is one that argues that complexity, in both general and restricted forms, can be meaningfully absorbed into heterodox discourse, retaining the 'richness' of critical thought while being formally robust.

Components of a complex ontology already exist within heterodox economics and political economy more generally. As Lavoie (2014: 16) notes, heterodox approaches adopt a systems view over the atomicity of the representative agent in mainstream frameworks, signalling a belief that reductionism abstracts away from the connections, interactions and dynamism that characterise social reality. A point of connection between the different types of complexity and the project of political economy is the decentering of a *homo economicus* as a self-interested, unitary being; that is, an agent has a context and history embedded in their behaviour, and that behaviour is only a minor part of system movement. Furthermore, general complexity provides an ontological base similar to the existing critical realism of PKE, but it clarifies some ambiguous terms (e.g., 'emergence', 'evolution') apparent in the latter through grounded, restricted processes translatable into formal ABMs and empirics.

While there is no universal criterion for a synthesis between theories, one measure is the degree of which there is a preservation or commensurability of ontology. The contention here is that the Minskian vision is already complex, but that complexity is implicit. The capitalist system in question is structured by agential firms, households and institutions that interact through financial and monetary spheres. These are networks of interaction at a meso-level of analysis, that produce cyclical fluctuations irreducible to any one agent. Fundamental Keynesian uncertainty is pervasive, partially expressed through the subjective value of risk imbued in debt contracts and the virtue of liquidity. The system is dynamically uncertain, feeding back into agent expectations. Individuals are boundedly rational, and the imperative for capital and profit accumulation opens up the possibility for emergent crisis through debt-financed investment. There is no permanent resolution nor equilibrium point to this system; it is nonlinear, dynamic and evolutionary, and so long as investment is a necessary component of a decentralised economy, crises will occur. The project of complexity allows a probing of these nonlinearities, dynamical and evolutionary characteristics, and consequently, addresses the outstanding problems associated with Minsky's theories.

1.4 Conclusion: Filling the gaps

Minsky's ontology, like many other Post Keynesian economists, is founded upon a vision of an open system comprised of a capitalist monetary economy. Minsky's oeuvre is largely concerned with endogenous cyclical fluctuations arising within financial markets, which works through the evolution of debt obligations in firm financing. Similarly, applications of financial complexity theory posit the significance of endogenous volatility, and attempt to pin-down explanatory causes by looking at agent networks, emergent macrostructures and

system dynamics.

The Minskian hypothesis is faced with the fallacy of composition, missing a crucial level of analysis between the microeconomics of investment, and the macroeconomic fragility that can result. Complexity research on the other hand, has the reversed problem of lax theoretical foundations with robust methodologies. Bringing these frameworks together alleviates these extant issues by forcing a reconsideration of some assumed processes, such as the dynamics of agent adaptation, speculation and equilibrium analysis.

Chapter 2

Micro-meso-macro in a Minskian complexity theory

The present chapter is an applied synthesis and demonstrates how overt positivism does not have to be the fate of complexity research. Networking theory and dynamical systems theory can be treated as extensions of a Minskian study of aggregate cycles, providing a fresh perspective on uncertainty, speculation and risk proper. Here, the focus shifts from theoretical consequences, to a detailing of micro-, meso- and macroeconomic dynamics under a Minskian complexity theory. Significant attention is paid to developing the meso-level, the analytical level between the decisions of an individual firm and the aggregate economy. The meso-level is characterised by network interactions, and can build on the existing ideas of Minsky through the insights of network theory. To do this, the assumption of system nonergodicity is explored and translated into a decision rule-based analysis.

Section 2.1 details the complex system assumptions employed in analysis, particularly around the role of system ergodicity in conceptualising Keynesian uncertainty. This allows a movement toward rule-based analysis as a method of tracing endogenous cycles to the behaviour of agents. Section 2.2 explores this avenue at the mesoeconomic level, demonstrating the role of social transmission and system architecture in the emergence of financial fragility. Inter-banking and firm networks are discussed to illustrate how risk and sentiment can spread through mesoeconomic architecture. Finally, Section 2.3 steps back to connect these principles to the macroeconomy, connecting the Minskian patterns of stability-fragility to the dynamical principle of a resilience-stability trade-off.

2.1 System assumptions and microeconomic principles

The use of microfoundations is a controversial point within heterodox economics, with Chick (2016: 99) noting that many heterodox theorists are suspicious of the orthodox tendency to base macro-analysis on microeconomics. Microeconomic axioms like the assumption of transitive preferences and convex production functions do not have a role in macroeconomics, but are used within principle-agent problems to proxy complex interaction (e.g., Kydland & Prescott, 1982; Smets & Wouters, 2003). The Sonnenschein-Mantel-Debreu and Arrow's impossibility theorem are examples of aggregate intractability that arises from basic microeconomic principles, but these are side-stepped by assuming rational expectations of a unitary representative agent.

Under a complexity approach, specifically aggregate complexity and agent-based modelling, microfoundations are necessary for explaining emergent phenomena. It is a method-

ological individualist framework that is distinct from the microfoundations of orthodox economics; the microfoundations of complexity are mutable, decentred, and not constrained to equilibrium conditions. As such, a more suitable descriptor may be to use the term 'microspecifications' from the agent-based literature (Adamatti, 2014: 89). The thorny issue of this conception of the micro-level is that the interaction between agents themselves may produce qualitatively different macrostructures, as a collective action can create a macroeconomic effect irreducible to the behaviour of one agent, e.g., the paradox of debt.

As Chick (2016) argues,

> The unsuitability of 'rational choice' theory to a macroeconomics based on uncertainty does not mean that micro-decision-making should be dismissed as irrelevant to macroeconomics it just has to be a microeconomics based on different principles. (Chick, 2016: 110)

So what microeconomic principles should underpin a Minskian complexity theory?

Toporowski (2006: 4) notes that this is a fundamental question to Minsky's own analysis, which attempted to found a theory of aggregate cycles on microfoundations independent of parametric changes. In other words, the microeconomics embedded in the instability hypothesis via the two-price theory of investment are constant across macroeconomic fluctuations, because the processes of interest are chiefly those intrinsic to capitalist structuration. It follows that a Minskian complexity framework requires microspecifications to flow from fundamental system characteristics. Microeconomic principles such as bounded rationality, heterogeneous agents, and the virtue of liquidity fall from the common precipice of system nonergodicity. The bridge between nonergodicity and these microspecifications comes through Keynesian uncertainty, as a nonergodic world is one that is uncertain in such a way that is unquantifiable, unlike risk proper.

2.1.1 The importance of the ergodic and nonergodic distinction

The ergodic axiom in orthodox economics ensures that there exists a steady-state equilibrium. Both ergodic and nonergodic processes are stochastic, but the former states that 'history does not really matter' (Dahms & Hazelrigg, 2012: 8). An ergodic system traverses along a path that is statistically representative of its constituent 'micro-states', akin to the law of large numbers (Auyang, 1999: 98). As a result, the trajectory of an ergodic system is not constrained by the motion of its component states, as both are statistically representative of one another. Birkhoff (1913, 1931) contributed the first ergodic theorem, which was built on by Neumann (1932) and introduced into economics through Samuelson (1948). This lead to equilibrium analysis being the norm, solidifying the standard use of linear programming in modelling, as ergodicity is congruent with the marginalist method of first-order approximations.

Alternatively, if a system or process is nonergodic, the trajectory is dependent on the movement of the micro-states, and so captures within it the sensitive dependence on initial conditions (SDIC) of dynamically complex systems. As such, there is path-dependency and 'history matters' (Dahms & Hazelrigg, 2012: 8). Complex socio-economic systems are often framed as nonergodic (e.g., Moore, 2006; Dahms & Hazelrigg, 2012; Davidson, 2005). The technical consequences of system nonergodicity mean that common simplifying mathematical tools cannot be used, such as the central limit theorem (CLT). The CLT requires that sample data be representative of the actual underlying population, according to the law of large numbers. Additionally, the second moment (variance) must be finite, to constrain the values to some range. However, if the system is nonergodic, the underlying population data may in fact be characterised by infinite variance, giving scope for statistical discrepancies between population and sample data.

Whether the underlying system is characterised as nonergodic or ergodic has significant consequences for theory. For example, the Efficient Market Hypothesis assumes that markets can be described as a stationary ergodic (Brownian motion) process, which translates into the assumption that asset prices are stochastic and independent of time. Because such processes are normally (Gaussian) distributed, the CLT can be employed. These assumptions are the basis for the no-arbitrage axiom required in financial market equilibrium; the condition that no exploitable price discrepancies exist between assets. To reach this no-arbitrage equilibrium, agents must be rational and profit maximising so that any pricing errors get instantaneously fixed. In other words, there is no uncertainty, or at minimum, any uncertainty is transient. If this is true, the only sources of price volatility are stochastic exogenous shocks or changes in market fundamentals - both of which are independent of the underlying ergodic process.

Conversely, a nonergodic view of financial markets suggests the continual presence of non-probabilistic uncertainty, as processes are historical, cumulatively changing over time. Pricing errors or shocks can have perverse impacts, instead of being instantaneously resolved. For instance, a collection of arbitrageurs attempting to smooth out any endogenous or exogenous shocks, buy (sell) when the price is low (high). Since the shock and subsequent actions affect all future returns, the arbitrageurs have created a cascade of events that they can never 'catch up' to, and instead inadvertently increase overall volatility in the long run (Mirowski, 1990: 297). Resultant is the fact that, 'one cannot accurately predict future behavior [*sic*] on the basis of past observed distributions' (Moore, 2006: xxv). In the Minskian instability hypothesis, the idea of nonergodicity is present in the framing of the traverse toward an economic stability - the forces of movement toward any given point hold forces of destabilisation, with uncertain contingent events accumulating over time (Minsky, 1986/2008: 197).

2.1.2 Keynesian uncertainty

Nonergodicity is the foundation for Keynesian uncertainty as presented by Keynes (1921, 1936), and relates to the fact that forecasts of the future state of the world are not compressible into a series of probabilities. Since probabilities are directly related to the evidence presented, an infinite range of probabilities about a single proposition can exist at the same time Keynes (1921: 2, 7). Keynes (1921: 30) suggests that the probability of some event occurring changes due to the arrival of new evidence or the general unfolding of history. The prior probability still exists as it forms from a set of knowledge and evidence that is *independent* of the new set. This is to say that knowledge about a proposition does not secularly increase in certainty over time if the outcome of that event or statement is not decomposable into a series of probabilities of 'objective chance', e.g., a roulette wheel is not 'uncertain' (Keynes, 1921: 477).

The manner in which individuals manage this fundamental uncertainty is highly differentiated, as each vision is influenced by an individual's unique subjective beliefs and experiences. Keynes (1921: Ch2, 3) discusses 'degrees of rational belief' as forms of subjective probabilities influenced by an individual's own heuristic rules gained from experience and thought, as well as external influences such as authoritative and institutional advice. Decisions are unlikely to be purely rational in the sense of being objectively correct. Knowledge is limited, and the sense of certainty around a proposition is primarily determined in relation to other propositions, all with varying degrees of subjective evidence - a notion associated with *bounded rationality*, an idea by Simon (1957, 1982) and extended by Sargent et al. (1993).

Minsky (1996: 361) points out that Keynesian uncertainty and bounded rationality are distinct however, and although the latter can extend from the first, it does not mean they are synonymous. Bounded rationality denotes the cognitively limited, but often sufficient, rules used to untangle a complex reality which may not be uncertain in the Keynesian sense. In fact, bounded rationality by way of information asymmetries has been adopted into the Knightian framework of orthodox economics. Under Knightian uncertainty, the difference between uncertainty and risk proper is differentiated, but involves a processual removal of uncertainties i.e., Bayesian learning. Here, forecasts tend toward the correct belief over time.

In *The General Theory*, Keynes (1936) turns to the role of uncertainty in financial markets. Uncertainty is non-numerical ambiguity of the future, which cannot be ascribed to a simple probability or risk calculation, because it often deals with subjective conjecture about things that cannot be known or the future path of an infinite number of variables. In this way, this form of uncertainty is completely independent of risk proper, with the latter being quantifiable, thus insurable, whilst the former is not. The famous example of the beauty contest illustrates this mode of thought Keynes (1936):

> [P]rofessional investment may be likened to those newspaper competitions in which the competitors have to pick out the six prettiest faces from a hundred photographs, the prize being awarded to the competitor whose choice most nearly corresponds to the average preferences of the competitors as a whole; so that each competitor has to pick, not those faces which he himself finds prettiest, but those which he thinks likeliest to catch the fancy of the other competitors, all of whom are looking at the problem from the same point of view. (Keynes, 1936: 156)

Keynes conceptualises investment behaviour as a guessing game, wherein choice to invest in stock is uncertain, dependent on predicting what other (uncertain) investors will do. Under this type of uncertainty, how to individuals form coherent expectations?

Within a Minskian complexity theory, Keynesian uncertainty can be thought of as shaping the individual decisions of investing agents. Along with the cash-flow considerations that determine the pace of external investment, the management of fundamental unsureness over the future requires behavioural rules to guide the decision-making process. As Axtell et al. (2016: 80) note, theorising around behaviour rules is a non-trivial undertaking, as the essential object is how agents, who have limited knowledge, learn from other agents whom also have incomplete information.

Further, system nonergodicity means that any outcome of a decision rule changes the macroeconomic path, akin to the sensitivity to initial conditions (SDIC) of dynamical complexity. As a result of Keynesian uncertainty, Walrasian equilibrium analysis becomes untenable, as the traverse towards some steady-state can itself hold forces that disrupt the macroeconomic trajectory (Minsky, 1976: 59).

2.1.3 Decision rules

In a clarification for *The General Theory*, (Keynes, 1937: 214-215) presents the ways 'we manage in such circumstances to behave in a manner which saves our faces as rational, economic [people]':

1. **The frequentist rule**: We follow a frequentist approach to forecasting the uncertain, basing predictions on the past that may have no relation to the prediction in question;

2. **The introspective rule**: We assume that the present state of the world is the same as that of the future; and,

3. **The conventional judgement rule**: We use the *wisdom of the crowd*, using the average or majority of total opinion as a guide.

All of these psychological devices are heuristic rules or 'rules of thumb', employed by individuals in the decision-making process. Although Minsky did not discuss at length

the significance of these rules, it is alluded to within the instability hypothesis. Minsky (1996: 361) argues that if mounting evidence against the viability of a decision rule becomes widespread, many agents can switch behaviours and create a sudden macroeconomic change.

Furthermore, decision rules play a role in the two-price theory of investment, primarily entering via the subjective value of liquidity. In Minsky's original form, the supply and demand price of investment is respectively found via current output price (markup over cost) and the price of capital and financial assets. Capital assets are valued according to realised cash flows, carrying costs, and the liquidity premium, the last of which relates to the feasibility of turning the asset into paper money. The liquidity premium connects capital and financial assets through the subjective value of money, as the insurance property of money or near-monies determines the willingness to hold an asset. There is thus an inherently speculative dimension embedded in the choice to forgo money today for future expected cash-flow, which requires the adoption of a decision rule that assesses the value of money.

In this sense, a shared valuation of the liquidity of financial and capital assets forms the basis of investment, implying there is a switch between introspective rules and conventional judgement along an aggregate cycle. To illustrate this, consider the scenario in which a firm seeks finance to extend production during buoyant macroeconomic conditions. Per the two-price theory, the firm mobilises existing cash-flows to internally finance, implying an introspective decision rule that is either rooted in historical performance or the assumption that the current heightened demand will continue indefinitely. Externally financing beyond this level requires the firm to face increased uncertainty, as the firm will be indebted to a lender for an extended period. As a result, the firm may draw on conventional judgement (e.g., majority opinion), motivating firms to move from a hedge to speculative position. Stable or expansionary macroeconomic conditions spur on a collective devaluation of money, as the fear of unexpected contingencies thus the virtue of liquidity declines, further pushing toward a Ponzi-dominated market. Inflation is, therefore, one of the markers of an overheating economy. In times of crisis, this process is reversed in a Fisherian debt-deflation, where households and Ponzi firms undertake 'distress selling' of capital and financial assets (Fisher, 1933: 342), corresponding to a sudden increase in the virtue of liquidity.

Nevertheless, there remain some outstanding questions. How does the strategic switch between hedge, speculative and Ponzi finance occur? Are these strategies socially transmitted? Furthermore, what are the conditions that support or diminish the spread of fragility-inducing decision rules?

2.2 Mesoeconomic principles

Under a complexity lens, the dynamics of decision rules are principally expressed at a mesoeconomic level, the mediating space of network interaction between the microeconomics of a single agent, and the aggregate economy. The meso-level can be characterised by a set

of hierarchically organised abstract rules, which gain coherence by relation to other rules:

> A system that is definably 'economic' in nature is reliant upon a structure of rules that are economic, i.e. that relate to the production and consumption of goods and services. However, economic rules are, necessarily, embedded in a broader environment of rules - variously physical, biological, cognitive, behavioural, social, ecological, legal, political, and so forth. [...] This simple observation goes some way to explaining why economic systems tend to be fantastically complex systems, and why evolution, rather than 'rational intention', is the principle source of transformational change and development. (Dopfer et al., 2004: 266)

This is to say that mesoeconomics avoids the fallacy of composition by focusing on a rule-based analysis, which attempts to explain system evolution as a result of endogenous rule changes. The 'meso-trajectory' of Dopfer et al. (2004: 271) is presented as a way to conceptualise this evolution, which traces the movement of a rule in a population. Social transmission via decision rules is one of the important vehicles of behavioural change within a decentralised capitalist market, and one way of conceptualising the 'animal spirits' of speculative investment.

2.2.1 Social transmission and animal spirits

Social networks transmit decision rules, determining their emergence, diffusion and retention across a relational space. The architecture of this space, or the network topology, is then a significant source of endogenous volatility, playing a role in aggregate fluctuations by structuring the social determinants of investment decisions. For instance, the role of interpersonal relationships on investment strategies is heavily documented, with research often adopting network analysis to track the social transmission of information (see e.g., Scott, 1991; Shiller, 1995; Panchenko et al., 2013). This approach may ground the notion of 'animal spirits', the speculative optimism and pessimism in markets that lead to self-fulfilling outcomes. Indeed, De Grauwe (2011) and De Grauwe & Macchiarelli (2015) use an agent-based model to demonstrate the role of animal spirits in the propagation of cyclical fluctuations, which is formally specified as a dynamically complex endogenous rule change in investment behaviours.

Dopfer et al. (2004: 356) argue that explanations for behavioural contagion and speculative herding can arise due to *decision rule cascades*, which suggests that movement of economic rules across social networks are not stochastic, but determined by the position of an agent in a topological social space. The strength of animal spirits is a product of its structural context, with the influence of any emergent decision rule dependent on the relationships of the first-adopter(s). A decision rule cascade is a type of meso-trajectory that traces the 'entropic degradation' of rules, producing aggregate cycles due to lags in

social transmission (Dopfer et al., 2004: 352, 353). For example, an investing agent may see a profit opportunity in a company, and purchases stocks under optimistic expectations. Other agents imitate this strategy and begin buying the financial assets in that particular industry. Entrepreneurial individuals, seeing a profit opportunity, gradually create new firms under the belief that aggregate demand is high. This over-saturates the market and creates a bubble-like situation with inflated financial assets. The influential first-adopter, as an experienced investor, sells their assets and retains a profit, while those who are at the bottom end of the cascade face sufficient losses due to lags in social transmission. This process can explain volatility clustering or 'hot spots' of speculative interest, even when it would be 'irrational' according to fundamentals analysis (Earl et al., 2007: 359-360).

2.2.2 The network architecture of banks and firms

An agent's choice to invest and bear more debt is reduced by Minsky (in Friedman et al., 1989: 178) to time-dependent introspection about past, current and future liability structures. In other words, agents exist within a historical context that cannot be divorced from the decision rules they adopt. The way in which Minsky illustrates this socio-historical context is through interconnected balance sheet relations, which connect both agents with themselves through time, as well as other agents along a network.

Networks constitute the meso-structure of the financial system, where the characteristics of individual agents and institutions are cohered through bounded interaction. Bounded rationality and a risk-averse decision rules only make sense if it is specified that the agent exists within a network with an upper bound on the range of influence. Similarly, any change in the liability structure of a firm must correspond to change somewhere else, i.e. a firm's on-take of bank-financed investment appears as an asset on the bank's balance sheet.

It then follows that the particular structure of interaction informs the extent to which endogenous fragility can arise. In a way, network structure, or topology, has always been a concern of political economy for this reason. Do markets tend towards a competitive outcome with low volatility when laissez-faire governance is followed? Alternatively, does the structure of capitalist relations tend to mutate markets into monopolies that require strong government intervention? Minsky (1986/2008: 355) argues in terms of the latter, and in particular, discusses the importance of a decentralised banking network in fostering finance to small-medium business enterprises.

Banks are agential profit-seeking institutions. If they are allowed to be oligopolistic, banks may choose to privilege finance to large corporations, in the pursuit for secured wealth (Minsky, 1986/2008: 355). The possibility of this was realised through the Riegle-Neal Act of 1994, which allowed banks to expand operations across state borders within the United States. The act was partially justified on the probability calculation that a centralised banking system, akin to an oligopolistic market structure, increased system robustness

against systemic risk (see Akhigbe & Whyte, 2003). Larger banks can efficiently absorb perturbations that smaller banks cannot. Similarly, idiosyncratic risks can be diversified across branches in different geographic locations, lowering the exposure to potential fragility.

Generally speaking, the interbank configuration allowed by the Riegle-Neal Act is a disassortative scale-free system: a few large banks are connected to a range of smaller firms and institutions, the latter group being less connected to one another, compared with the large banking hubs. Regarding networking topology, each agent is represented as a 'node' in the network, with relationships denoted via 'links'. Each node has a number of links, called its 'degree', with a 'degree distribution' being the aggregate probability distribution of degrees. A scale-free system is characterised by a degree distribution that is power law distributed, which implies high inequality between node degrees (see Ozkan-Canbolat & Beraha, 2016).

Contrary to the basis of the Riegle-Neal Act, the Financial Crisis demonstrated that failure of the large hubs can create a near-absolute cascade of system breakdown. Although the disassortative interbank network has a lower chance of spreading illiquidity risk from the smaller less connected nodes, an illiquidity crisis in an oligopolistic bank with a large degree can amplify crisis effects, due to its connectivity. This is a resilience-stability trade-off apparent in the interbank network, also known as the trade-off between the ability to 'load redistribute' through risk diversification, while creating a contagion of risk. As Roukny et al. (2013) argue, this may imply that disassortative scale-free banking networks may not have any more protection against crisis and fragility than a decentralised competitive network; that is, a network with many small nodes, connected relatively evenly via links.

Within the Minskian framework, a corporate bank is a profit-seeking institution that actively shapes the terms of financing through risk considerations. If it is believed that load redistribution reduces idiosyncratic risk and provides a buffer to systemic risk, the bank may choose to lower the criteria for firms and institutions, especially during an expansionary or tranquil phase. A large bank may choose to privilege lines of credit to similarly large firms, as monopolistic or oligopolistic corporations have high cash flows, and can hypothecate more assets.

Returning to firm networks, firm sizes are characterised by a power (Zipf) law with exponent equal 1 (Axtell, 2001). This power law distribution means that large monopolistic firms tend to grow faster than small firms, having a disproportionate share in national aggregates (Gualdi & Mandel, 2016: 2). Although an intuitive result, it suggests that firm size distribution is not governed by a stochastic growth process which, if it were, would result in a (long assumed) lognormal distribution (Axtell, 2001: 1818). It also means that minor endogenous or exogenous perturbations can cascade to create instability, if the shocks occur within the monopolistic hubs. Consequently, a network of smaller competitive firms are sufficiently more robust against economic instability and exogenous shocks.

Gabaix et al. (2006) suggest that a Zipf distributed firm population can create endoge-

nous volatility through the trades of large institutional firms and can explain the stylised fact that asset prices follow a power law of exponent equal 3. If there is something of a cubic law of absolute returns ($|ret|$) following the form $Pr(|ret| > x) = kx^{-3}$, where k represents an unremarkable constant, it means that the probability of an extreme event, i.e. financial crisis, falling 10 and 20 standard deviations from the mean is respectively $5^3 = 125$ and $10^3 = 1000$ less likely than a two standard deviation event (Gabaix, 2016: 190). Comparing this with the Gaussian distribution, which would suggest that it is 10^{22} and 10^{87} times less likely, the existence of a cubic law suggests events such as bubbles and crashes may not simply be outliers, but closer to the norm (ibid. 190).

Gabaix et al. (2006) hypothesise that market illiquidity causes large firms to deleverage, which due to their size, cause stock market crashes. In the instability hypothesis, market illiquidity may be created by a speculative boom, which stymies liquidity through balance sheet and portfolio changes, such as the acquisition of debt financing or assets. Minsky (1970: 27) suggests that within illiquid markets, sudden increase in liquidity preference corresponds to a rapid decline in confidence, leading to a Fisherian debt deflation. As firms are Zipf distributed, this means that a few or even a single monopolistic investor(s) can trigger a severe decline in asset price in a fragile system, which also absorbs the notion of a decision rule cascade arising from an influential agent.

An obvious parallel here can be drawn from the beginnings of the Financial Crisis, which was marked by the bailout of two hedge funds owned by the investment bank Bear Stearns in June 2007. The funds traded with relatively new financial derivative products in the shadow banking sector, collateralised debt obligations. Considering the Ponzi-like position of Bear Stearns, selling the collateral was the only way to recover liquidity. The act of selling itself caused a sudden cascade of deleveraging, even though only a minority of the collateral was sold. This nonlinear impact may be traced to the size and reputable influence of Bear Stearns (Ryback, 2009: 3) and the existing fragile state of the U.S economy. Because the derivatives themselves are complex through layered bundling and securitisation, pinning down the source of risk was impossible, leading to a 'relentless landslide' (Bellofiore & Halevi, 2011: 8).

2.3 Macroeconomic principles through the resilience-stability trade-off

The trade-off between system stability and resilience is an idea borrowed from dynamical theories of ecological change, which states that increased biological diversity (i.e. heterogeneity in population and environmental conditions) can dually raise volatility and resilience (Holling, 1973). Dai et al. (2012: 1175) note that diminished volatility in ecological systems is a marker of potential collapse, particularly around the length of time required for a system to return to its steady-state. As the system reaches the point of crisis (the tipping point),

the length of recovery from minor perturbations becomes longer, meaning the system is less volatile. This phenomenon is known as 'critical slowing down' in the dynamical complexity literature and is an early warning sign of an abrupt movement (a phase transition) toward an unstable state (Scholz et al., 1987).

Applying this idea to the Minskian theory of financial fragility requires a clarification over what stability and resilience mean in an economic context. In Minsky's own words,

> Economies are complex multidimensional systems. Robustness and resilience are two attributes which a system may possess. Robustness means that small shocks to the system are absorbed without much difficulty; resilience means that a system bounces back after a shock. Fragility negates robustness and resilience: it, therefore, means that the response of the system to small disturbances or small changes can be large and that after a disturbance the system does not bounce back. (Minsky, 1995: 199)

For the purpose of analysis here, Minsky's terminology will be slightly changed. Robustness and resilience will be treated as synonymous terms, both characterising the ability to manage endogenous or exogenous changes and return to a 'tranquil' state. Specifying stability is a far more tricky and ambiguous undertaking.

As Issing (2003: 1) notes, defining financial stability is difficult, as it places assumptions over what the regular functioning of the economy is. The Minskian approach adopts a vision of capitalist economies as self-destabilising, underscoring any statement on stability as necessarily transient. This is further complicated by the fact that economic stability is treated as a product of hedge financed units. It is plausible to suggest that a hedge-dominated economy is both stable and resilient, meaning no trade-off may exist during the early expansionary phases of the aggregate cycle. However, if stability is measured with respect to asset price and output volatility, the trade-off is theoretically tenable. This is to say that if high volatility characterises a system, the system is usually more resilient as agents tend to be more risk-averse and pursue hedge financing. Therefore, any crisis-like events, especially those that are exogenous (e.g., an oil-price shock) are absorbed by securely financed firms.

Diminishing output and asset price volatility may cause a spike in risk-taking behaviours, under the belief that systemic risk is low. This endogenous increase in systemic risk is denoted the 'volatility paradox' by Brunnermeier & Sannikov (2014), and explains how secular changes in optimistic decision rules can create a resilience-stability trade-off situation. During times of low volatility, increased risk-taking is seen through financial innovation (e.g. new derivative products) and 'experimentation with liability structures', both of which stem from the belief that uncertainty is low (Minsky, 1986/2008: 199). The inflow of circulating money causes inflationary pressures, corresponding to a steady rise in capital and financial asset price, while strong demand supports aggregate output. As this trend continues, the

system is marred by lowered resilience due to increased debt. Overall increases in debt are not necessarily the problem in itself; it is more so that the amortisation schedule locks-in a firm's repayments over an extended period of time. As repayment time is extended in the aggregate, the resilience of the macroeconomy is reduced, as any slight change in interest rates or an exogenous supply-shock can create a protracted crisis.

The most prominent example of the resilience-stability trade-off may be the period of low volatility preceding the Financial Crisis, the 'Great Moderation'. From approximately the mid-1980's to the beginning of the crisis in 2007, U.S. output, inflation and employment volatility was remarkably low. Although tracing the emergence of the crisis to over-optimistic debt financing (in housing) is only a partial explanation, the implied volatilities of financial assets 'suggest that the perceived risks in financial markets had shrunk to extremely low levels by 2006' (Bean, 2010: 296).

The resilience-stability trade-off can thus be used to theorise between the connection of Minsky basic cycles and super-cycles. Recall basic cycles are the fluctuations in capitalist systems marked by procyclical leverage that roughly follows the hedge-speculative-Ponzi schema and lasts approximately a decade (Palley, 2011: 2-3). This is contrasted to the super-cycle, which tracks the gradual evolution of increased fragility across several basic cycles (ibid. 8). The super-cycle thus often corresponds to institutional and regulatory changes towards a deregulated market environment, which becomes re-regulated after a protracted recessionary phase. Following the dynamical complexity literature, lowered volatility of basic cycles through a decline in amplitude or increase in duration may indicate critical slowing down of the system and lowered resilience. As a result, identifying the patterns of basic cycles may serve as an early warning sign of a potential downturn in the super-cycle.

2.4 Conclusion: Connecting the analytical levels

Complexity supposes that the connection between micro-, meso- and macro-levels, and the interactions within these levels, are the components of interest in systems analysis. The consequence of this is that traditional tools employed for analytical tractability become irrelevant; equilibrium analysis, normal (Gaussian) distributions, rational expectations and the representative agent are the most obvious victims of adopting a complexity framework. It also implicates aspects of Minsky's own work, as he adopts a representative agent to justify the two-price theory and thus the financial instability hypothesis.

The technical argument presented in this chapter attempts to rectify the analytical levels within a Minskian framework, by bringing in decision rule analysis and network theory. Aggregate fluctuations and excess volatility arise from the financing decisions of boundedly rational firms, who face an uncertain future and look to heuristic rules for guidance. The adoption and dissemination of rules depend on the architecture of the economy and its subsystems, such as the distribution of firms and interbank networks. As heuristics guide

investment behaviour, speculative leveraging decisions can create socially-spread contagion effects, resulting in cycles driven by optimistic and pessimistic 'animal spirits'. As a result, a rational decision at the level of the firm can create a maladaptive (e.g., crisis) outcome if all agents follow suit, broadly illustrated through a resilience-stability trade-off.

Chapter 3

Theoretical considerations in simulating complex economies

The ideas presented so far bring forward the notion of Keynesian uncertainty in determining the meso-level behaviour of firms and institutions, working through aggregate and dynamical approaches to aggregate cycles. In a concretely non-equilibrium framework, the ontology or 'vision' underlying this thesis is one of evolutionary dynamism, which is intractable and cannot be holistically broached due to the epistemological limits of general complexity.

The modelling methodology of the agent-based framework directly confronts this epistemological quandary, and must wade through the problem of balancing parsimony and realism. Agent-based models (ABMs) are computational tools that use programmed microfoundations to simulate emergent macrostructures, and do not face the standard tractability constraints of the general equilibrium framework (Farmer & Foley, 2009: 685). Despite suggestions that ABMs constitute a novel modelling paradigm (cf. Giulioni et al., 2017; Cogliano & Jiang, 2016; Arslan, 2017) they must first address the problem of how to reduce the high-dimensionality associated with heterogeneous agents and multiple spheres of interaction, while balancing reality and model parsimony.

This final chapter assesses Minskian agent-based models (ABMs) from a Minskian complexity theoretic perspective, to identify the benefits and deficiencies in computational treatments of the Minskian hypothesis. As a methodological counterpart to complexity economics, ABMs developed alongside restricted complexity discourse, but have been picked up by both Post Keynesian and New Keynesian practitioners. Amongst strong developments in computational methods, the complexity perspective is at risk of being minimised or discarded entirely, with some ABMs turning into stylised dynamic stochastic general equilibrium (DSGE) models. That is, there may be a return to general equilibrium steady-state analysis within ABMs, which relieves the computational weight of intractability, but moves research into 'solving' endogenous fluctuations, rather than understanding the possible conditions of which fragility manifests.

ABMs are briefly introduced in Section 3.1, compared with and posed as a better alternative to current DSGE and stock-flow consistent (SFC) models. Methodological issues are also discussed, namely the problems of model calibration (estimation) and the study of baseline scenarios as a complexity-minded replacement for equilibrium analysis. Moving to specific Minskian ABMs in Section 3.2, the models are outlined relative to the themes in Chapter 2, namely heterogeneity, speculative 'animal spirits', and network architecture. Critically assessing these models in Section 3.3, however, requires a return to the arguments set out in Chapter 1.

3.1 Why agent-based modelling?

Models are reduced-form representations of social reality, employed for pedagogy, theoretical exploration and policy-advice. Following general complexity, every conception of reality is a model of some sort, whether expressed via narrative reasoning or equation-based formalisms. Mainstream economics prefers the latter, envisioning a modelling space governed by the axioms of general equilibrium. This space is built up by *adding* elements such as production and consumption spheres, as well as abstract mechanisms to impose, for example, rigidities (e.g., Greenwald & Stiglitz, 1989; Mankiw & Reis, 2007) and the (short-run) neutrality of money (e.g., Lagos & Wright, 2005). Minsky (2015/1982: 61) denotes this the 'village fair paradigm', which reduces a complex financial and monetary economy into a simple, resolvable market.

Conversely, ABMs do not necessarily have any resolution by way of a closed form solution, because the microfoundations are not analytically constrained in the manner of standard economics (Salzano et al., 2007: xv). Using computational methods, ABMs are flexible in the specification of agents, institutions and interactions, which create emergent patterns as the model is simulated. This modelling framework is often orientated toward a generative process analysis, which according to Epstein (2006: 19) involves asking, 'how could the decentralised local interactions of heterogeneous autonomous agents generate the given regularity'? As such, ABMs can be treated as a computational experiment in itself or a testing arena for some hypothesis about social reality (Phan & Varenne, 2010).

Aggregate complexity has co-developed alongside the agent-based framework, most obvious when considering the essential characteristics of ABMs. Recall aggregate complexity involves analysing the adaptive and evolutionary patterns that emerge between a boundedly rational individual and a broader network. Similarly, Epstein (2006: 20) presents five core characteristics of ABMs:

1. Agent heterogeneity in preferences, heuristics and social networks, that evolve over time;
2. Decentralisation in agent behaviour;
3. Interactions that occur on an explicit mathematical space;
4. Agents have bounded interaction; and,
5. Agents are boundedly rational, and cannot know the exact path or macro-structures that govern their actions.

ABMs have recently absorbed insights from the stock-flow consistency (SFC) literature of PKE [1], through agent based-stock flow consistent (AB-SFC) models (e.g., Kinsella et

[1] For a review of the SFC literature, see Caverzasi & Godin (2013).

al., 2011; Chakraborti et al., 2011; Berg et al., 2015; Caiani et al., 2016). AB-SFC models respond to the need for an alternative modelling paradigm, while attempting to resolving outstanding problems associated with the SFC literature. SFC models use a highly aggregated accounting framework to track monetary stocks and flows, but are liable to the fallacy of composition, the Lucas critique, and have been critiqued as empirically spurious (Kinsella, 2011). Additionally, the argument presented in Chapter 2 highlights the importance of agent heterogeneity and endogenous rule changes in the emergence of financial fragility, of which SFC models cannot handle due to static and exogenous behaviour rules.

Recent ABMs (e.g., Caiani et al., 2016) use stock-flow consistency as an internal validation check, to ensure any stock or flow of money is accounted for, i.e. a liability has a corresponding asset on a balance sheet and vice versa. These AB-SFC models also adopt insights from econophysics and econobiology, as the tools of standard economics are not well equipped to manage non-equilibrium multi-agent frameworks (e.g., Kinsella et al., 2011; Chakraborti et al., 2011; Berg et al., 2015).

3.1.1 Replacing equilibrium with baseline scenarios

The use of equilibrium within macro-modelling is conceptually comforting. It creates model determinacy through the presence of a solution, or at least a constrained range of solutions when there are multiple equilibria. General complexity and the Minskian framework suppose that Walrasian equilibrium does not exist in any meaningful sense, bringing into question the relevance of equilibrium analysis[2]. ABMs present an alternative modelling methodology to equilibrium solutions, by establishing a baseline scenario and then 'experimenting' with model changes. Although a multi-agent framework does not necessarily negate the possibility of closed-form equilibrium solutions (e.g., Assenza et al., 2010), many ABMs follow a procedure of (i) specifying the theoretical microfoundations of interest, (ii) calibrating parameters to produce a baseline simulation of stylised facts, and (iii) systematically testing alternative scenarios by changing relevant variables or behavioural rules.

Akin to an experimental 'control', accurate estimation of the baseline scenario is key to a robust model. However, the method of establishing a baseline is a point of theoretical divergence; an ABM can turn into a stylised DSGE model through the use of representative agents in estimating the parameters of the baseline scenario, which can be solved for an equilibrium-like steady-state solution. The consequence is model simplicity through ergodicity, characteristic of the mainstream approach.

In the context of computational models, the estimation procedure refers to the process of assigning values to model parameters that reflect empirical regularities or data. Follow-

[2]Furthermore, Walrasian price equilibrium given utility maximising agents and convex production functions is intractable within computational economics (see Roughgarden, 2010) with some orientating research toward computational proof of non-existence (e.g., Roughgarden & Talgam-Cohen, 2015). This is a form of *computational complexity*, that falls under restricted approaches, but is unfortunately out of the scope of this paper.

ing Richiardi et al. (2006: 20), 'estimation' and 'calibration' of an ABM can be treated synonymously, as both relate to the procedure of configuring model parameters. It is imperative that the initial estimation be empirically robust if ABMs are to be considered tools for policy-making. Incorrect or biased estimation can lead to spurious model results, which is an underlying problem in the ABM literature as calibration methods are sometimes left unexplained (Caiani et al., 2016: 388). Computational DSGE models, as the standard class of orthodox models, have the benefit of having extensive literature on estimation procedures and thus an array of generalisable techniques (see e.g., Gomme et al., 2013). ABMs are comparatively less developed, but research is ongoing regarding finding a standard estimation procedure (e.g., Caiani et al., 2016).

There are several significant roadblocks to a standard procedure. Firstly, modelling methodologies are heterogeneous, and no uniform standard is currently accepted. Secondly, ABMs can handle many more parameters than DSGE models and can result in a model that is nonergodic and thus algorithmically unsolvable. Algorithmically derived equilibrium solutions offer formal closure by binding values to a unique or range (i.e. multiple equilibria) of steady-states. This reductionism makes the system probabilistically tractable and reduces the system path to a narrow range. In nonergodic ABMs, the system path is not unique, so choosing a baseline scenario can become an *ad hoc* or arbitrary choice between an infinite range of possible trajectories. Put differently, the baseline may not be robust.

The two primary methods of getting around the robustness problem in ABMs are:

1. Systematically changing parameters to bracket a solution that creates the phenomenon of interest or replicates stylised facts, which is simulated numerically. Doing so generates a *sufficiency theorem*, but is manually intensive to the point of being 'prohibitively slow' (Grasselli & Li, 2017: 2). It is also open to the curse of dimensionality, as continual runs of a complex ABM with high dimensionality has computational limits (Axtell, 2000). Nevertheless, this method retains nonergodicity, is not constrained by equilibrium concepts, and has proven to be a successful tool in PKE (e.g., Dosi et al., 2010).

2. Using the *master equation* approach of statistical mechanics to create ergodicity. This method involves aggregating agents into groups, to create a statistically 'average' representative agent. From here, system movement is reduced to a set of differential equations that represent, in probabilistic terms, macroeconomic trajectories. The ABM becomes analytically solvable as system states are compressed in an ergodic manner, resulting in the possibility of a steady-state. The master equation can be thought of as a blend of econophysics in a New Keynesian framework, and has been shown to significantly reduce computational burden (Grasselli & Li, 2017).

The sufficiency theorem approach retains nonergodicity as a connecting concept between complexity, ABMs and Minskian theories. Conversely, master equations are a simplifying

device that turns the many-body problem of ABMs into a representative agent problem, skipping over the meso-level of analysis entirely. Justification for the master-equation approach stems from mean-field theory, which states that interactions converge to a statistical average captured in the representative agent (see Grasselli & Li, 2017). The model becomes ergodic, and Keynesian uncertainty is ruled out.

The master equation approach gives primacy to the solution of a model rather than the constituent processes, such as rule-based learning and network interactions. For example, Di Guilmi et al. (2015), adopt the master equation framework in a Minskian ABM, using numerical simulations and equilibrium solutions to analyse the role of heterogeneous agents in leverage and capital accumulation cycles. Use of a master-equation allows the determination of the long-run stochastic path of the artificial economy, which exhibits Minskian cycles of pro-cyclical leverage. It is found that if firms are more sensitive to changes in cash flows, cyclical patterns are pronounced, as aggregate debt tends to rise more strongly in response to a relatively small increase in cash flows. However, Di Guilmi et al. (2015) removes the interaction between agents as a source of macroeconomic volatility. The model itself does not tend toward equilibrium but is solved for steady-state values, giving priority to stability conditions over the underlying meso-level processes influencing investment strategies.

Even withstanding the problems associated with a sufficiency theorem approach, it retains nonergodicity and by definition, Keynesian uncertainty, putting weight on the conditions of aggregate cycles over model closure. The sufficiency theorem aligns with Minsky's call for simulation as an experimental device:

> The short durations of crises means that the smoothing operations that go into data generations as well as econometric analysis will tend to minimise the importance of crises. Because of such factors, it might be that the most meaningful way to *test propositions* as to the cause and effect of financial instability will be through simulation studies, where the simulation models are designed to reflect *alternative ways* that financial instability can be induced [emphasis added]. (Minsky, 1970: 4, as cited in Giulioni et al., 2017: 297-298).

3.2 A review of Minskian ABMs

In most cases, the ABM literature can be decomposed by the estimation procedures used. New Keynesian approaches tend to follow a master equation method that uses the baseline as a quasi-steady-state equilibrium (e.g., Di Guilmi et al., 2015; Caiani et al., 2016), while Post Keynesian models can be partially identified by the utilisation of a sufficiency theorem (e.g., Dosi et al., 2010; Seppecher & Salle, 2017). In terms of testing and replicating the Minskian fragility hypothesis, both approaches have been taken (cf. Assenza et al., 2010; Seppecher & Salle, 2015; Seppecher et al., 2016). Although differences in methodology somewhat block

deep comparison of model results, if it is accepted that retaining a complex ontology is an essential philosophical backbone of ABMs, Minskian models using a sufficiency approach already have a head start.

What follows is an assessment of various ABMs that attempt to capture Minskian dynamics using the sufficiency theorem approach to trace the processes governing aggregate cycles. The central point here argues that increased complexity is a double-edged sword, increasing sensitivity to network interaction and dynamical complexity, but at the cost of parsimony - discussed by the end of the chapter.

3.2.1 Agent heterogeneity and credit networks

The role of agent heterogeneity in macroeconomic stability is presented by Assenza et al. (2010) in a simple Minskian ABM, extended with the addition of credit networks via Delli Gatti (2012). These models highlight the importance of firm heterogeneity and network interactions as proximate mechanisms of financial fragility; that is, the agent heterogeneity and the degree to which they are connected are hypothesised to impact firm behaviour and macroeconomic stability.

Assenza et al. (2010) compares a numerically simulated heterogeneous agent model with a simplified master equation approach, a representative agent model. The heterogeneity among firms is defined through their financial condition, imputed through a stochastic equity ratio drawn from a normal distribution with positive variance. In the representative model, the distribution of the equity ratio has zero variance, equivalent to rational expectations. In both cases, the causal driver of behaviour mostly echoes the Minskian formation: financially constrained firms seek capital accumulation and profit maximisation. However, expectations are one-period backward looking (Assenza et al., 2010: 192-195), limiting the extent to which historical context and memory play a role in investment decisions. Firms are financially constrained regarding investment, and lender-borrower risk is captured via a countercyclical external finance premium viz. Bernanke et al. (1999) and Kiyotaki & Moore (1997) and interest rate on loans. These factors determine the pace of investment and credit-equity financing. The representative agent case of Assenza et al. (2010: 198-199) aggregates into an IS-LM framework, employing equilibrium analysis around the linearisation of investment ratios and the endogenous determination of interest rates. Although also analysable through an IS-LM approach, the heterogeneous agent case employs nonlinear equations with stochastic shocks and is instead numerically simulated.

Model results demonstrate that financial heterogeneity is a dampening factor in cyclical fluctuations, comparative to the representative agent case. In the former, output gap, interest rate and average equity ratio volatility are markedly reduced. The explanation for increased stability with heterogeneous agents stems from the negative correlation between mean and variance in heterogenous agents: in the textbook IS-LM case of a representative

agent, expansionary monetary policy increases investment, increasing mean equity ratio and leaving variance unchanged. If agents have heterogenous financing conditions, a decline in interest rates positively impacts the cross-sectional mean of equity ratios by reducing the interest burden on outstanding credit debts. As a result, the variance of the cross-sectional mean declines, leading heterogeneity to be a factor in lowered aggregate volatility. At first glance, these results appear orthogonal to resilience-stability trade-off outlined in the previous chapter. However, the model of Assenza et al. (2010) does not generate protracted recessionary periods by design, but may be indicative of the period preceding 'irrational exuberance' (Shiller, 2000) marked by low volatility in returns.

Assenza et al. (2010) provide an example of a Minskian ABM that is not complex. It does involve heterogeneous agents that create an emergent reduction in macroeconomic volatility, but there is no agent interaction nor evolution. Additionally, there are no opinion dynamics that simulate 'animal spirits', with heterogeneity and homogeneity relegated to stochastic equity ratio rather than behaviour rules. Furthermore, the specification of one-period adaptive expectations dismisses the importance of historical path-dependent trajectories in the formation of decisions. The problem of interaction, however, is partially addressed through a network theory extension of the model by Delli Gatti (2012).

Delli Gatti (2012) extends the Assenza et al. (2010) model to include a complex credit network, which allows the determination of investment to be related to agent robustness, i.e. equity ratios, and the robustness of related agents. Agent actions and impacts, such as bankruptcy, can therefore impact other linked nodes depending on the agents' degree and weight of the links. Following Battiston et al. (2012) (as cited in Delli Gatti, 2012: 13) this is represented as a 'law of motion of robustness' of an agent $i = 1, 2, .., N$ in time t:

$$da_i = \sum_{j=1}^{k} W_{ij} a_j - a_i + \frac{\sigma}{\sqrt{k}} \sum_{j=1}^{k} W_{ij} d\xi_j - \alpha q(k)$$

Where a is the robustness of agent $i \neq j$, W is the weight of a link between agents, k represents the degree of an node, and ξ is an idiosyncratic shock with standard deviation σ. α is the amplitude of a decline in robustness, with q the probability of a continued decline dependent on the degree, k.

This equation states that the change of robustness of node i (da_i) is dependent on the net robustness of neighbouring nodes ($\sum_{j=1}^{k} W_{ij} a_j - a_i$), the impact of a idiosyncratic shock ($d\xi_j$) across the network ($\frac{\sigma}{\sqrt{k}} \sum_{j=1}^{k} W_{ij} d\xi_j$), and some positive feedback mechanism ($-\alpha q(k)$). It formalises the theory that increased network connectivity allows for the dispersion of idiosyncratic risk via risk sharing, at the cost of escalating systemic risk. If the degree of a node is increasing, i.e. k increases, the robustness da_i increases. However, $-\alpha q(k)$ allows for positive trend reinforcement, acting as a 'network based financial accelerator' (Delli Gatti, 2012: 13).

This idiosyncratic-systemic risk trade-off is consistent with the ideas of Chapter 2, along with other ABMs that find a similar result (cf. Riccetti et al., 2013): 'the larger the number of connected neighbours, the smaller the risk of an individual collapse but the higher systemic risk and therefore the lower network resilience' (Delli Gatti, 2012: 15). It is a partial inclusion of aggregate complexity via networks, but the 'positive trend reinforcement' is conceptually underdeveloped. Under the Keynesian perspective, this gap may be addressed through an investigation into the opinion dynamics underlying sentiment.

3.2.2 Opinion dynamics and animal spirits

Opinion dynamics can be modelled through decision-rules, as outlined in the previous chapter. The ABMs considered below attempt to simulate Minskian (basic) cycles by specifying simple or complex decision rule processes as the drivers of optimism and pessimism. For this paper, simple and complex rules are differentiated by how agents adopt the rule. Namely, simple endogenous rule changes can arise from an individual's assessment of their situation without mesoeconomic interaction with other actors. These introspective rules are trivial; simple rules are indiscriminate (no learning) and usually involve a one-step backward looking (adaptive) expectations function, based on economic aggregates, as in Assenza et al. (2010). In contrast, complex rules involve social transmission (e.g., social learning), or iteratively established through trial-and-error. In these scenarios, the model can simulate agent cognition under a dynamically adaptive process.

A toy model of simple decision rules is presented by Ormerod (2002), which successfully replicates the cumulative distribution of the size of recessions in the United States. Namely, it attempts to explain an earlier finding that recessions follow a power law-like relationship between frequency and size of duration (see Ormerod & Mounfield, 2001). The model specifies heterogenous firms under uncertainty, differentiated by size drawn from a power law distribution, operating on a complete topology - all firms (nodes) are connected to one another, causing every individual firm to have complete information about the prior period. As such, the network is not complex, but as will be outlined, it is nonergodic through the inclusion of Keynesian uncertainty. The firm makes two decisions in every period to determine (i) production output growth rate, and (ii) whether they are optimistic or pessimistic.

A reduced form of this model is presented by Ormerod et al. (2007: 203-204), who denote output growth rate ($x_{i,t}$) of agent i in time t, as the sum of the prior period sentiment (y_i) of all firms, weighted by size (w_i), with a stochastic factor ($\varepsilon_{i,t}$) to represent uncertainty[3]:

$$x_{i,t} = \sum_i w_{i,t-1} y_{i,t-1} + \varepsilon_{i,t}$$

[3]Notation has been modified for consistency.

Notably, $\varepsilon_{i,t}$ is drawn from a normal distribution and is also established independently for each agent. Keynesian uncertainty thus enters into the model by allowing agents to have independent, stochastic signals.

Sentiment $y_{i,t}$ is determined by a simple decision rule:

$$y_{i,t} = (1-\beta)y_{i,t-1} - \beta\left[\sum_i w_{i,t-1}x_{i,t-1} + \eta_{i,t}\right]$$

This states that current sentiment is oscillating according to the subjective weight β a firm gives to sentiment and aggregate weighted output in the prior period. The negative sign for β allows this dampened oscillation: given a constant β, rising aggregate (weighted) output eventually results in a downward revision in sentiment leading to cyclical fluctuations (Ormerod, 2002: 779). Additionally, the term $\eta_{i,t}$ represents a normally distributed stochastic factor, drawn independently for each firm.

This model demonstrates that a simple oscillating opinion dynamic can simulate endogenous cycles, empirically robust concerning the power law-like characteristic of recessions. It is made inherently uncertain by specifying the independence of stochastic factors between agents and there is no maximising principle in the model. The fully connected topology negates the possibility for systemic risk to spread via the architecture of the system, as was specified for interbank networks in Delli Gatti (2012). It follows to ask whether further including restricted complexity can provide a more robust understanding the constituent features of aggregate cycles.

De Grauwe & Macchiarelli (2015) form an ABM to explore how changes in heuristics and sentiment create aggregate fluctuations, finding that the incorporation of opinion dynamics generates self-fulfilling endogenous cycles. Relative to New Keynesian models of self-fulfilling cycles, which adopt informational rigidities to force inertia under rational expectations and Bayesian learning, De Grauwe & Macchiarelli (2015) use endogenous rule switching that does not converge to an equilibrium point - there is dynamical complexity. Agents experience contagion in heuristics, which become correlated in optimistic expansionary and pessimistic contractionary phases of the cycle. De Grauwe & Macchiarelli (2015) thus present a model closely aligning to a Minskian complexity theory, relative to the previous models explored. Unfortunately, model calibration is mostly unspecified by De Grauwe & Macchiarelli (2015), with only the estimated parameters of the model presented.

The simulated macroeconomy is set up through aggregate demand-supply (AD-AS) equations and an inflation targeting Taylor rule, determining the exogenous interest rate set by the central bank. Populating the model are agents whose positions (e.g., firms, households) are captured within the AD-AS. These agents adopt and switch between two decision rules plus some subjective weight, with the weight reflecting the historical performance of a rule and memory of the agent. There is a fundamentalist rule, which bases expectations on the steady-state value of the output gap and target inflation rate, and an extrapolative

rule that uses the prior observation for output and inflation to form forecasts (De Grauwe & Macchiarelli, 2015: 97). The determination of weights is endogenous, meaning the weight ascribed to a rule is increased (decreased) if it performs well (poorly). Rule switching is then an iterative process, requiring a continual comparison between the two rules. Sentiment is defined by the bias of the forecast: if it is biased upward, the agent is optimistic and if it is biased downward, they are pessimistic.

Model results show that 'waves of optimism and pessimism' are more persistent with money endogeneity, leading to larger swings in the output gap (De Grauwe & Macchiarelli, 2015: 109). The length of memory is found to have an impact on the 'animal spirits', as no opinion-led cycles occurred in the case of no memory and perfect memory (rational expectations) (De Grauwe, 2011: 439-440). This finding echoes the suggestion of Minsky (1986/2008: 199, 299), who stated booms and busts are somewhat dependent on our ability to forget past crises, even though overall, we learn from mistakes. The overall Minskian hypothesis is supported: numerical simulations show that expansionary periods increase the value of firms' financial assets, leading banks to reduce interest rate spread and creating a self-fulfilling boom. In a downturn, an increase in the spread on loans corresponds to generalised pessimism.

The message here is that a model with complex opinion dynamics can be successfully simulated without adopting a master-equation approach. It is not a resolute determination of 'laws' governing endogenous cycles, but the above ABMs do raise points of note in the ways cognition and learning can be modelled in a dynamic context. These ideas are further developed within the ABMs of Seppecher & Salle (2015); Seppecher et al. (2016, 2017); Seppecher & Salle (2017), which represent Minskian models sensitive toward complexity. Although extensive treatment is not given here, Seppecher & Salle (2015) and Seppecher et al. (2016) are critically appraised as state-of-the-art ABMs, opening up discussion for future research.

3.2.3 Toward complexity models of Minskian dynamics

Behavioural AB-SFC models are developed by Seppecher & Salle (2015) and Seppecher et al. (2016), to simulate the emergence and dynamics of endogenous medium-term cycles using the sufficiency theorem approach. The first model by Seppecher & Salle (2015) is in a similar spirit to that of De Grauwe & Macchiarelli (2015); swings in optimism and pessimism are specified through an opinion dynamic, translating into macroeconomic patterns of stability and deleveraging crises. The second model of Seppecher et al. (2016) uses a similar modelling environment (i.e., set up and Jamel program), but focuses on complex adaptation and learning among interacting agent. Both macro-models are specified in firm, household, financial and central banking sectors, but only involves a single bank, a point that will be returned to. For ease of discussion, the former model is referred to as the 'deleveraging' ABM, and the latter is denoted the 'learning' ABM. As of the writing of this paper, these

represent leading ABMs that adopt complex systems thinking within a Minskian model.

The 'deleveraging' ABM finds that simulated crises reflect Fisherian debt-deflation scenarios, with macroeconomic recovery dependent on income, prices and wages (Seppecher & Salle, 2015: 3787). Agent heterogeneity is an emergent product of the model, with initial microspecifications (e.g., asset endowments, expectations functions) being homogenous across agents. Seppecher & Salle (2015: 3772) presents the 'procedural rationality' and 'heterogeneity' as the foundational concepts of the model, with the former relating to the evolution of bounded rationality through time, and the latter relating to the heterogeneity of opinions.

The opinion dynamics of households have both introspective and 'animal spirits' components; that is, for n total households, household i assesses their individual state of (un)employment and also looks outward to the consumer sentiment of $h < n$ local households, in every period. The probability that the household depends on introspection, or relies on the majority opinion (pessimistic or optimistic) is respectively $1 - p$ and p. Similarly, for m total firms, opinions dictate the level of financing undertaken through a single bank. Firms calculate the wage cost of full employment in their production, and if this wage bill is higher than current cash flows, a firm borrows. Each firm has a leverage target, the goal ratio between debt and total assets, with optimistic firms having high leverage objectives, and pessimistic having low leverage objectives. The 'animal spirits' component of opinion is identical to that of households but is introspective in regard to the level of excess inventories, which proxies output demand. If a firm is experiencing low inventories (high demand), the firm is optimistic, and vice versa. The same probabilities as the household apply, i.e. firms look at their own situation with probability $1 - p$, and adopt majority opinion with probability p.

The baseline scenario of the model replicates some stylised macroeconomic facts. It can produce procyclicality in consumption, employment, changes in inventories, and the velocity of money Seppecher & Salle (2015: 3780). Additionally, the firm size distribution is not normally distributed and exhibits positive skewness, indicating that it may be power law distributed as is outlined in Chapter 2. The simulation also reveals six phases of a business cycle, with aggregate volatility increasing as opinion dynamics are strengthened, i.e. rising probability p that majority opinion heuristics are employed (Figure. 3.1):

1. The economy enters a stable phase, denoted the 'corridor of stability';

2. There is an economic slowdown that causes a decline in profits and employment, with inflation turning to deflation;

3. The economy 'bottom's out' with maximum unemployment and deflation, and a minimum profit share';

4. There is a recovery;

5. Boom with high inflation and low unemployment;

6. The economy returns to the corridor of stability.

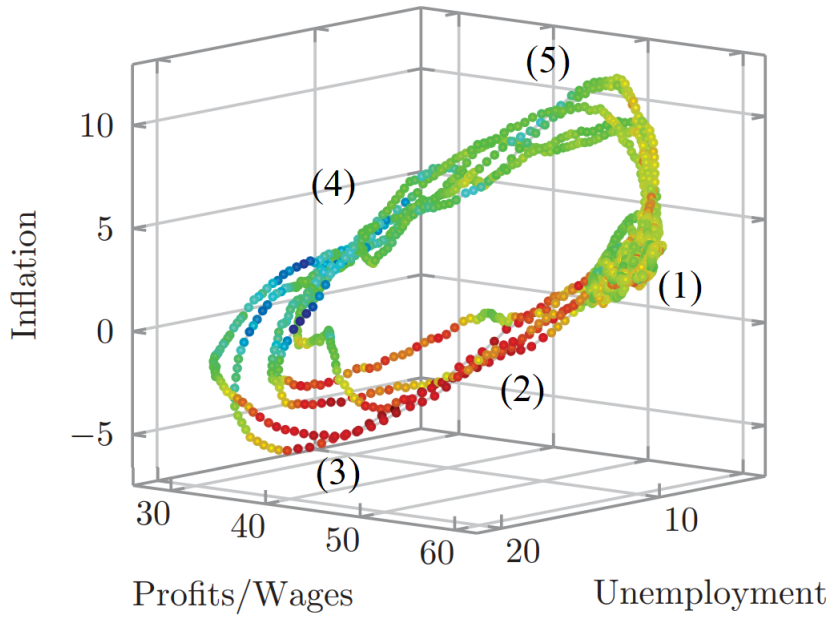


Figure 3.1: Phases of the business cycle with respect to inflation, the profit share and unemployment (Seppecher & Salle, 2015: 3780).

The cyclical pattern reflects movement toward and away from a Fisherian debt deflation, endogenous stimulated by contagion effects of pessimistic opinions in those initially optimistic. There is no equilibrium analysis whatsoever, though the corridor of stability mirrors the Robinsonian term, 'periods of tranquillity' borrowed by Minsky (1986/2008: 197).

Results of the ABM are consistent with Minsky's diagnosis of aggregate fluctuations. Namely, Seppecher & Salle (2015) find that macroeconomic recoveries are stronger with inflexible nominal wages, as rigidities cause a increase in real wages during the deleveraging process. A rise in real wages stimulates a demand-driven recovery through support to consumption. Minsky (1986/2008: 197-198) suggested that declining wages during a deleveraging period erode the profitability of firms by diminishing consumption, causing failure to service outstanding debt obligations. An alternative scenario with increased nominal wage flexibility is simulated and is found to cause mass firm bankruptcies and a systemic banking crisis, causing the ABM to stop (Seppecher & Salle, 2015: 2786).

Further refining these ideas, Seppecher et al. (2016) build a Minskian ABM with complexity insights. Namely, the model exhibits sensitivity to a general complexity ontology and considers evolutionary aggregate complexity through an adaptive learning mechanism,

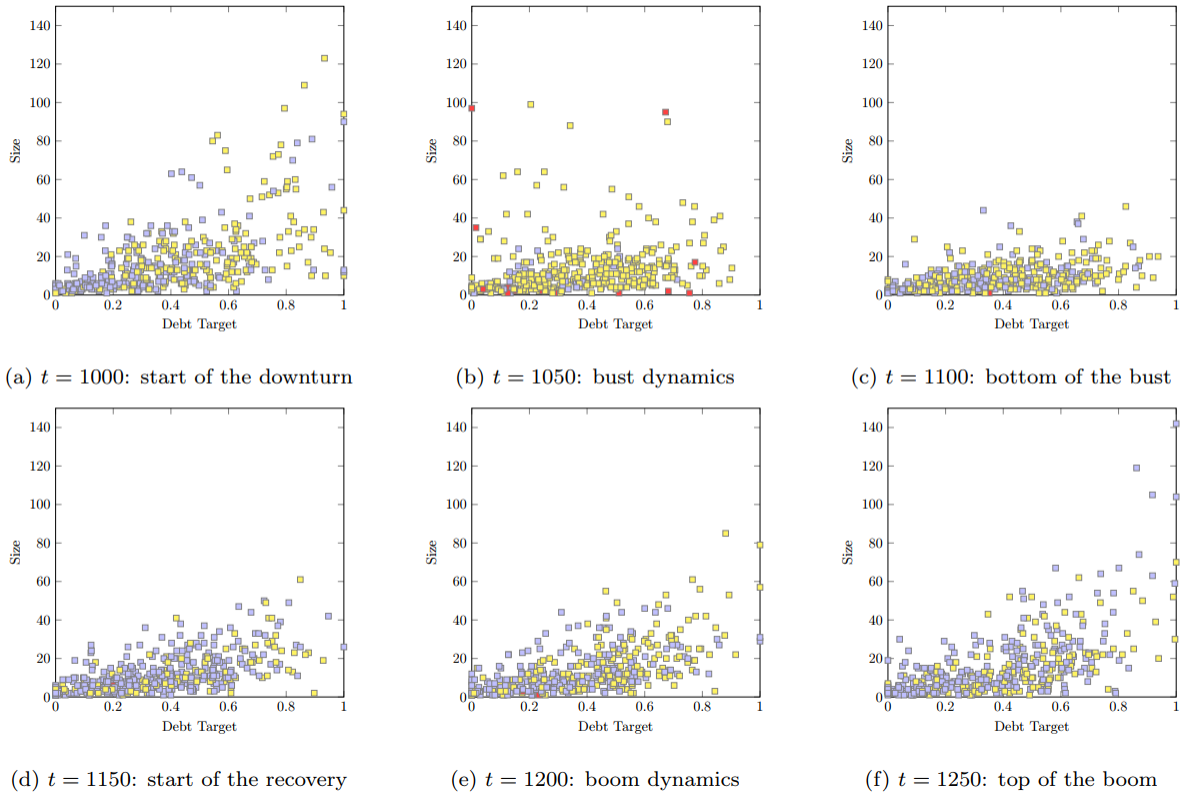
the 'blanketing shotgun process' (BSP) of Alchian (1950). The BSP states that agents consciously adapt leverage strategies via imitating successful agents, with the objective of positive profits as opposed to maximisation. Seppecher et al. (2016: 11) outlines three mechanisms of the BSP: (1) positive profits (rather than maximal) reinforce behaviours and act like a natural selection process, (2) mimesis of the endogenously determined successful firms, (3) innovation due to modifications to the imitation of successful strategies. Unlike standard versions of Darwinian evolution in economics (e.g., genetic algorithms), the BSP allows non-convergence to arise from imperfect imitation, which is also an avenue of innovation.

The aggregate complexity ideas of Holland (1992b,a) acts as a way to confront the general complexity of social reality, specifying the economy as a complex adaptive system due to the reflexive learning capacity of agents. The theoretical object of Seppecher et al. (2016) is a system of continual adaptation, with macrostructures coproduced by agents that experience and produce feedback effects. Because of this continually changing modelling environment, the comparison of agent strategies between qualitatively unique state spaces is difficult, as each strategy is only understood relative to the context it existed (Seppecher et al., 2016: 9).

The BSP produces pro-cyclical leverage ratios, and behavioural convergence during a recessionary period. Behavioural convergence arises as the sustained indebtedness of high leverage targets begins by affecting large firms, and then spreads through imitation to smaller firms, resulting in systemic fragility. Figure 3.2 illustrates these changes, with each square denoting a firm and the upper right side represents large firms with high debt targets. The blue, yellow and red colours respectively denote Minskian hedge, speculative and Ponzi firms.

Although there is always a concentration of small and low debt targeting firms, the beginning of the downturn (a) and the maximal point of the boom (f) exhibit dispersion toward large firms and high debt levels. The simulated economy then undergoes a 'brutal' correction as large firms go bankrupt and risk-taking agents re-evaluate their strategies (Seppecher et al., 2016: 30). Furthermore, enlarged aggregate debt is driven by a minority of firms that are disproportionately large. Accordingly, a severe Fisherian debt deflation occurs (observed in Figure 3.2 (b) and (c)), due to an endogenous rise in commercial bank interest rates in period $t = 1000$, which corresponds to the beginning of the downturn (Seppecher et al., 2016: 32).

The outstanding limitation of this model is the specification of the one-bank banking sector. The 'deleveraging' model has a 'passive' fully accommodative bank that recapitalises debt of bankrupt firms (Seppecher & Salle, 2015: 3779). Although the bank is extended in the 'learning' model through allowing multiple types of loans (e.g., short-run non-amortised, long-run amortised), it remains 'very stylized [*sic*]' (Seppecher et al., 2016: 18, 23). As discussed in the previous chapter and illustrated by Delli Gatti (2012), a multiple bank



(a) $t = 1000$: start of the downturn (b) $t = 1050$: bust dynamics (c) $t = 1100$: bottom of the bust

(d) $t = 1150$: start of the recovery (e) $t = 1200$: boom dynamics (f) $t = 1250$: top of the boom

Figure 3.2: Share of hedge (blue), speculative (yellow) and Ponzi (red) firms across the cycle, from period 1000 to 1250 (Seppecher et al., 2016: 29).

network is imperative to understanding the dynamics of risk. Through the Minskian lens, a bank is an agential unit who actively discriminates through credit rationing and the interest spread. This critique, among others, is taken up to conclude this chapter and point forward for recommendations for future research.

3.3 The limitations of ABMs

The computational limits of ABMs can be dealt with via reducing a sphere or several sectors of the simulated economy. Seppecher & Salle (2015) and Seppecher et al. (2016) do this by employing a highly stylised banking sector with only one bank. All models discussed use this reductionism to reduce computational burden. There is limitation of agent interaction (Assenza et al., 2010), adoption of a complete topology with low-cognition agents Ormerod et al. (2007) and a restriction of rule switching between two choices, e.g., fundamentalist and extrapolative (De Grauwe & Macchiarelli, 2015) or introspection and conventional judgement (Seppecher & Salle, 2015). Removing a banking network is particularly problematic however, because it removes the possibility of analysing inter-bank networks as a

propagation mechanism for risk. As the earlier chapter outlined, the architecture of the banking system may play a significant role in dampening or amplifying systemic risk, and negation of a complex banking structure in an ABM of financial fragility could limit the fecundity of model insights.

These reductions bring forward the problem of model parsimony in ABMs. In theory, ABMs can simulate complex multi-sector dynamics from highly detailed microfoundations, spanning many variables and tracking their movement. OSullivan et al. (2012: 113) argue that in this case, 'we simply replace one difficult to understand phenomenon - the world itself - with an equally hard to understand model'. The causal relationships may be difficult to untangle in a complex ABM, with extensive parameters overfitting the data in the baseline calibration. The response to this, and the opinion put forward in this thesis, is that ABMs are orientated toward process analysis rather than prediction. Increasing the complexity of a model is less of a problem in this case, because the ABM acts as an experimental scenario to validate hypothesis. In this case, however, ABMs may be critiqued as 'thought experiments' comparative to parsimonious and empirically robust DSGE models. This critique must delve into policy implications, which is out of the scope of this paper, but it may be the case that pedagogical exploration of ABMs must precede policy; ABMs are still embryonic compared to contemporary DSGE models, so there is significant space to cover in terms of the limits and successes of computational modelling.

Another associated problem with ABMs is the heterogeneity in method. There is no uniform protocol in model analysis, exemplified by the difference in master equation and sufficiency theorem approaches. This problem goes beyond model design, as even the software programs used to execute simulations are heterogeneous in programming language and created *ad hoc* for a specific researcher(s) or model, e.g., the Jamel program is used only for the works associated with Seppecher & Salle (2015) and Seppecher et al. (2016). Although the methodology is robust, Richiardi et al. (2006: 17) comment that this modelling freedom has led to 'anarchy (in terms design, analysis and presentation)'. These are not problems that the complexity framework can solve because these are problems of the epistemological freedom of complexity itself.

These problems highlight the necessary role for a guiding theory or theoretical framework in economic modelling. In this paper, the complexity framework acts as a lens to fill the gaps between analytical levels in a Minskian framework. It builds on an existing foundation and reworks meso-level details in such a way that is sensitive to ontological and restricted complexity. Although this paper does not build and present a novel ABM, it may be a useful suggestion that ABMs begin to similarly work through existing frameworks, or at minimum, find an acceptable standard of model design.

3.4 Conclusion: Strengthening the links

A Minskian complexity theoretic approach requires a methodology that captures nonergodicity at its most basic level. Keynesian uncertainty is the natural result of model nonergodicity, and ABMs that remove this facet by employing a representative agent viz. a master equation approach turn ABMs into stylised DSGE models. To avoid this and increase the system complexity of a simulated economy, the sufficiency theorem should be employed, which replaces equilibrium analysis with process analysis. Nevertheless, there are computational limits to doing so, a concern that also flows into model design.

The ABMs presented do not draw absolute causal lines, but open points of interest in terms of modelling endogenous fluctuations. Assenza et al. (2010) and Delli Gatti (2012) demonstrate that agent heterogeneity is a dampening factor in terms of aggregate volatility, with network interaction creating a trade-off between the mitigation of idiosyncratic risk and the increase in systemic risk. Ormerod et al. (2007) allows for Keynesian uncertainty within a simple decision rule model, and De Grauwe & Macchiarelli (2015) demonstrate how complex adaptive rules create self-fulfilling swings in output and inflation. Finally, Seppecher & Salle (2015) and Seppecher et al. (2016) exemplify a state-of-the-art complex ABM of Minskian dynamics. These represent models that are complex, drawing primarily on the insights of aggregate complexity and econobiology. Although all the models discussed are heterogeneous in methodology, those that absorb complex systems thinking give a heightened understanding to processes, rather than simply describing how simple specifications can produce endogenous cycles.

Conclusion

In a post-crisis world faced with rapid computational advances, it is not surprising that many theorists have suggested complexity and ABMs pave a way forward in economics (e.g. Colander et al., 2003; Farmer & Foley, 2009). As separate frameworks, Minskian and complexity approaches have asymptotically converged; both hold similar conclusions with respect to the core sources of financial instability and the need for enlarged financial regulation, even whilst adopting distinct epistemological and methodological frameworks. Theorists like Rosser Jr (2006, 2010) have argued for a unification between complexity and Post Keynesian frameworks, hinting at Minsky as a potential entry point into exploring the endogenous, evolutionary nature of financial fragility. Cross-fertilisation between frameworks is seen in the recent agent based-stock flow consistent models of Seppecher et al. (2016), whom investigate the evolutionary process of imperfect learning as the source of aggregate fluctuations.

The cyclical emergence, expression and curtailment of financial fragility are complex phenomena, and it is fitting that the theory and methodology used to conceptualise aggregate fluctuations be sensitive to this complexity. This thesis provides an example of one way this can be done, by joining the Minskian hypothesis and complex systems thinking.

A complexity interpretation of Minsky's theories has been fruitful in two central regards. Firstly, financial complexity economics, whilst producing empirically robust and novel methodologies, does not have concrete ontological precepts unique to economics. In other words, complexity theory is a systems theory with strong linage in computational methods, but it does not constitute an economic theory. Secondly, Minsky has been critiqued as subjecting his theories to the fallacy of composition (Lavoie & Seccareccia, 2001: 83), and did not formalise his ideas into empirically testable models during his lifetime. Minsky, endowed with a pre-analytic vision built upon Keynes and Schumpeter, has the strong theoretical foundation that complexity lacks.

The primary focus of this thesis surrounds the development of a meso-level of analysis. It works through the microfoundations provided by Minsky in the financial instability hypothesis and the two-price theory of investment. Mesoeconomic principles, illustrated through decision-rule analysis and network interaction, add depth to the Minskian oeuvre by point to possible resolutions to the fallacy of composition. Speculation under uncertainty need not be abstract, metaphysical terms. Decision-rules can be concretely defined following Keynes (1921), and set up through ABMs as the causal determinants of 'animal spirits - the speculative swings in optimism and pessimism.

There must be a warning however: complexity is methodologically strong, but agnostic in its orientation toward economic theory. Because of this, there is a sufficient threat that complexity becomes (i) synonymous with one concept, i.e., 'emergence or 'dynamical systems, or (ii) employed as a methodology, without acknowledging ontology or epistemology. If either of these paths are taken, complexity is a project of mainstream economics,

or a transdisciplinary field that is inapplicable to understanding economic phenomena. As a fairly embryonic discipline, the tools of econobiology and econophysics can be cherry-picked and successfully absorbed into a general equilibrium framework. Networking theory has no fundamental principles orthogonal to general equilibrium, and ABMs can be turned into stylised DSGE models through the master equation. To combat this, there must be a sensitivity to a complex ontology and epistemology. Simplifying tools, such as the central limit theorem and the master equation are untenable if it accepted that social reality is complex, uncertain and nonergodic. However, if general complexity does indeed allow for pluralistic method, and posits the importance of local narratives - why should these tools be discarded?

The central limit theorem and other simplifying principles (e.g., convex utility functions) suppress the realm of theory building through axiomatic instrumental rationalism. In the social sciences, axioms allow privileging of one mode of thought over another, and force not only model closure but also dialogical closure. Culture, power, ideology and human inventiveness cannot be compressed into stochastic processes, and the economy cannot be 'solved' through a first-order approximation. There is no cognitive division between humans as emotional beings and as maximising agents. Both enter into economic processes, the latter is just 'nicer' to model.

Furthermore, mainstream economics treats methodology as social reality - at least to a degree sufficient to cause Lucas (2003: 1) to comment, '[the] central problem of depression prevention has been solved, for all practical purposes, and has in fact been solved for many decades'. Faithfulness to the general equilibrium theory of Arrow & Debreu (1954) has enforced tractability as the forefront of concern, creating a secular movement towards a rhetoric that supposes the economy tends to move toward a Walrasian equilibrium. The project of complexity, within a heterodox framework, is to enforce the division between reality and representation. All conceptions, whether aggregate complexity models of speculative contagion or dynamical models of chaotic financial markets, are representations. Treating them *as* reality is a conceptual misstep, and bringing heterodox discourse into complexity analysis can alleviate this problem. Heterodox thought in complexity economics conceptualises the macroeconomy as a network of interaction with potentially maladaptive outcomes. Stylising such complexity into functions and equations requires consideration over what statements are being made about the nature of social reality.

To conclude, it should be briefly mentioned that the bridge between PKE, complexity and ABMs is only one of many. Indeed, the structuration of feedback processes between the micro- and macroeconomy echo aspects of ecological Marxism, particularly around the notion of internal contradictions. The systemic conflict of adaptations at distinct analytical levels has also been compared to the Hegelian dialectic by Zwick (1978). Network interactions may be reworked under a poststructuralist/post-Marxist lens through interactionism, performativity and agency within the dimensions of the capitalist structure. Future re-

search may choose to follow these routes and add to the much needed theoretical richness of complexity in political economy.

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