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Review

A Systematic Literature Review of the Impact of Complexity Theory on Applied Economics

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Abstract: A systematic literature review is used to explore the relationship between complexity theory and economics. Broad search terms identify an unmanageable large number of hits. A more focused search strategy follows the PRISMA protocol and screens for Economics branded publications, and with key words for different applications of economics occurring in the abstract. This results in a distinct group of 247 publications. One hundred and twenty-two publications are excluded due to inclusion criteria or a lack of relevance. The remaining 113 are analysed for (1) use of complexity theory concepts, (2) types of methodology and methods, and (3) the applications for macro, meso, and micro issues. The publication with the greatest frequency of resulting articles is Complexity, closely followed by Ecological Economics. The highest annual citation ratio for a single article was 33.88. Complexity theory concepts included: non-linearity, system interactions, adaption, and resilience. Many developed a meso application, rather than solely focusing on macro or micro designs. Agent Based Models (ABMs) were popular, as were general systems models following the practice of the late system theorist, Donella Meadows. Applications were interdisciplinary and diverse, including world system models that linked macroeconomics to climate and sustainability, as contrast with micro and meso models trying to explain the complexity of agent-based behaviour on specific organisations or higher-level processes.

Keywords: complexity theory; economics; public policy; systematic review

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1. Introduction

Today's policy makers are faced with unprecedented challenges in tackling their immediate priorities of economic growth as well as how to approach other long-term issues suhch as climate change, energy security, and public health amongst others. For issues with many interdependent factors ('wicked problems'), it is difficult to determine drivers as multiple factors may produce similar or unidentical outcomes. For this reason, it is becoming more ubiquitous across the economic scholarship that understanding complexity offers a new science in which economic systems are understood as complex systems which cannot be judged using traditional linear analytical frameworks and methodologies. In light of these emerging complex policy challenges, advancements in economic conceptions have led to the development of 'non-orthodox' economic thinking with the labels heterodox and/or post-Keynesian economics (Lee and Lavoie 2012). Here, there is a growing scholarship on new ways of thinking that provide complementary, and alternative, perspectives to the equilibrium assumption of economic modelling. Within this economic paradigm lies the assumption that, amongst other things, economic systems are dynamic and oscillate between periods of stability and chaos, making them hard to predict.

Complexity theory is known to have had a growing influence on the broader social sciences in recent decades with increased citations that demonstrate this (Byrne and Callaghan 2013). Complexity theory was first developed in the physical sciences influencing the development of scientific concepts and methods for better understanding of unstable and difficult to predict systems such as meteorology (Lorenz 1963). Given the indeterminate nature of many social science phenomena, with novel behaviour and events resulting from a diversity of social interactions, many scholars soon saw the potential for complexity theory to assist in the explanation of the collective behaviours of societies and economies. Complex systems demonstrate a high level of uncertainty with low agreement between and across systems with regard to the causes of systemic pressures and the potential solutions to resolve such pressures (Bernardo and Smith 2009). This suggests an amount of irreducible uncertainty exists within the system (Sornette 2006). The uncertainty experienced within complex systems denotes non-linearity between cause and effect. This approach to thinking highlights properties that demonstrate features of complexity including, sensitivity to initial conditions and path dependency, emergence and self-organisation, feedback and feedback loops, and dynamic behaviours, as well as the interactions between these properties. Such an approach to economic modelling goes beyond the traditional orthodox approach where systems are seen to share identical patterns of behaviour, with interactions averaging each other out.

Castellani and Gerrits (2021) updated Map of the Complexity Sciences argues that Complexity Theory and Economics became increasingly linked from the 1990s onwards. The Santa Fe Institute (https://www.santafe.edu/ accessed on 20 July 2022) founded in 1984 was the first international scientific research institute dedicated to the study of complex adaptive systems. It succeeded in attracting leading scientists from across the world to consider important interdisciplinary science questions. Seminal academic leaders in this field included: Holland (1992), Kauffman (1993). Such scholars were ambitious in their desire to expand the new interdisciplinary scientific framework to cover the major social and economic challenges of the day. An economics program started in 1987, with much emphasis on the boundaries of the discipline, and the potential contribution of the interdisciplinary complexity science to economics. Fontana (2010), in a seminal historical summary of the impact of Santa Fe on economics, summarises three key impacts: dynamics, computational, and connectives. Complex dynamics is concerned with mathematical changes in economics with the developments to model chaos, sensitivity to initial conditions, and bifurcation. The focus here is on nonlinear approaches. Computational modelling primarily includes the development of agent-based modelling (ABM) allowing for a much more complex consideration of the behaviour of economic agents. Connective explanations are interested in the relational aspects of the economy such as positive and negative feedback and the operation of networks.

With this backdrop in mind, we use the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to comprehend the impact of complexity theory on applied economics. Before commencing this, we use an initial exploration to identify the most cited and highly influential scholars who have affected the metatheoretical union of complexity theory with general economics. We then proceed to make an original and substantial contribution, through the use of PRISMA to identify where this fusion of complexity theory with economics is having the most applied influence. In particular, we identify impacts in the use of microeconomics, including in business, management and organisations, and in macroeconomics, incorporating also political and policy-based interventions. There are also meso applications that link micro and macro in innovative ways. The paper structure is as follows, the subsequent section explains the method of using both an indicative literature search and a more structured systematic approach. Next, we present our results with a discussion on the most cited relevant scholars and PRISMA findings highlighting methodological trends as well as the thematic application of specific complexity concepts across our reviewed documents. Finally, we provide some concluding remarks.

2. Research Method

To assess developments in the application of complexity theory in applied economics, we undertake a two-step approach to data collection and review. First, we use Google

Scholar as an initial search tool to explore the broad relationship between scholars and publications that link complexity theory with economics and to observe some quantitative citation evidence about the most important scholars and source material. Google Scholar is used for this indicative purpose because of its wide breadth of coverage, and relatively limited ability for the researcher to control and manipulate the search focus. Google Scholar only offers limited text search options (i.e., publication title, or text from the whole article) and uses automatic search algorithms to find what should be the most useful and relevant examples (Beel and Gipp 2009). The date of the search is 18 July 2022. The search term is: allintitle: complexity OR "complex systems" OR "complex adaptive systems" AND economics. It yields 523 references. We use this to construct an indicative summary of the major scholars who influence the use of complexity theory in economics.

Second, a focused systematic literature review is conducted to identify applied influences of complexity theory in economics research. As noted by Liberati et al. (2009), systematic reviews and meta-analyses are useful for summarising evidence in an accurate and reliable manner. The explicit use of systematic procedures to identify selected literature reduces bias, thereby providing reliable findings from which a researcher can draw conclusions and provide recommendations (Oxman and Guyatt 1993). This approach helps researchers keep up-to-date with topical developments while allowing readers to judge the quality of reporting, through the evidence-based rationale provided (Moher et al. 2016). In this study, our systematic review of relevant literature was undertaken in accordance with the reporting techniques outlined within the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol (PRISMA) (Moher et al. 2009). Initially adopted in the medical sciences, the PRISMA protocol offers a set of procedures for the collection and reporting of systematic reviews and meta-analysis. PRISMA consists of four-phases, that is (a) document identification; (b) screening, (c) eligibility and (d) inclusion (see Figure 1 below for a flow diagram). These steps are aimed at improving the reporting of systematic reviews and meta-analysis. As outlined by Liberati et al. (2009), the PRISMA guidelines require a researcher to: (i) explicitly outline the research objectives with areproducible methodology; (ii) undertake a systematic search to identify studies that meet the eligibility criteria; (iii) validate the included studies; and (iv) present a synthesis of the content, characteristics and findings of studies included.

In this systematic review, we utilised a combination of the Elsevier Scopus ('Scopus') and Web of Science (WoS) database to search for publications in selected journals—imposing some further restrictions. Scopus is Elsevier's largest citation and abstract database with peer-reviewed academic literature that cover the areas of social sciences, life sciences as well as health and physical sciences. Similar to Scopus, WoS is an academic citation and indexing database that provides access to journals covering the arts and humanities disciplines, sciences, and social science. The use of both databases offered a wide interdisciplinary coverage in the identification of specific research outputs. Both Scopus and WoS also provide filtering options for the researcher to control the search focus. To ensure a focus search scope, and to capture only relevant documents that fall within the theoretical parameters of the study, we generated the following search string to identify documents with the mention of "complexity theory" OR "complex systems" OR "complex adaptive systems" in the document keywords. From this search string, a combined total of 135,610 documents were identified across both databases. In order to filter for only relevant papers, we restricted our search to documents that included the initial search string in only the publication title, AND econ* OR complex* in the publication source title. This restriction allowed for the identification of publications in journals with a thematic focus on economics and complexity. Likewise, additional restrictions were placed to include policy OR management OR organization OR finan* in the abstract and further limiting this to include only publications in English[1]. These additional restrictions provided a sample of publications with 'real world' applications, rather than 'theoretical conceptualisations'. After removing duplicates, a subset of 242 documents were identified. The data from Scopus and WoS was then extracted as a .csv file (comma-separated values) for further screening.

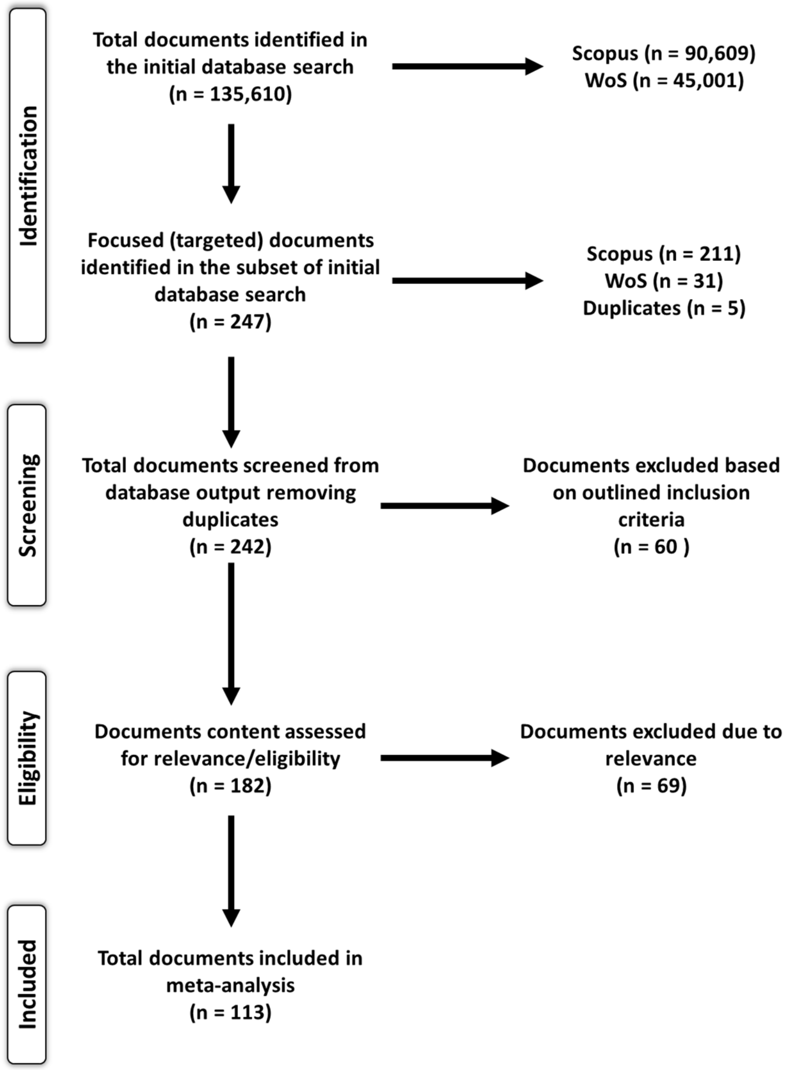

Figure 1. Literature Collection using the PRISMA Protocol.

Data screening and eligibility were two-part, first, we examined the abstracts of each document to detect and remove irrelevant literature. From this, an initial 60 documents were excluded from our analysis as the content of these publications are not openly assessible to the public domain. The second screening consisted of an examination of the full text of each document. At this stage, we developed an eligibility criterion based on the relevance of the publications (i.e., a direct focus on the application of complexity theory in the areas of applied economics, management, policy or finance). We also utilised publications impacts as both Scopus and WoS offer numeric values on the number of citations each publication has had. Lastly, the document type (i.e., Article, Review, etc.) were also consider in our criterion. From this, an additional 69 documents were removed from our analysis. Three publications were classified as Editorial, 55 documents were classified as either Conference Papers, Proceedings or Note, and the remaining 11 publications were either not contextually relevant or dated prior to 2019 with little research impact (no citations). Figure 1 (above) provides an overview of the document collection process using the PRISMA framework.

Table 1 below shows the top 15 frequently occurring publication titles for the documents included in our meta-analysis. Overall, *Complexity* has the most journal publications considered in our sample. This journal publishes studies that contribute to discussion on complex systems across a broad range of disciplines. For journals with a direct focus on economics, *Ecological Economics* features the most and is promoted as covering the situation of economics within ecology and the importance of ecological values to micro and macroeconomics. The *International Journal of Production Economics* deals with the interface of management and production, including manufacturing and engineering, and is marketed as an interdisciplinary journal. This has similarities with *Engineering Economics* and *Agricultural Economics*.

Table 1. Top 15 Journal Outputs: Frequency of Occurrence.

Journals	Total
Complexity	28
Ecological Economics	9
Ecological Complexity	7
International Journal of Production Economics	7
Construction Management and Economics	3
Engineering Economics	3
Handbook of Computational Economics	3
Journal of Economic Dynamics and Control	3
Journal of Physics: Complexity	3
Journal of Systems Science and Complexity	3
Cambridge Journal of Regions, Economy and Society	2
Complex Adaptive Systems Modeling	2
Complexity International	2
Journal of Economic Behavior and Organization	2
Journal of Economic Issues	2
Total Number of Journals included	*47*

3. Results and Discussion

3.1. Initial Exploration

One of the most cited is a book by Beinhocker (2006) entitled: The origin of wealth: evolution, complexity, and the radical remaking of economics with 2242 citations. Beinhocker is currently a professor at the University of Oxford. His book links economics with evolutionary biology and the thermodynamic laws of physics, therefore replicating some of the Santa Fe influence of seeing the natural sciences as important to economics. The core ideas of his book are summarised on page 97, Table 4.1. Economic systems are dynamic, nonlinear and far from equilibrium. Economic agents are diverse individuals with incomplete information who are subject to errors and biases. They adapt their behaviour. The economic interactions between agents can be partly understood through their changing networks of connections. Micro and macroeconomics are joined by the emergence of behaviours and interactions. The economic system evolves through differentiation, selection and amplification towards novelty and complexity. In the conclusion of his book, he makes a case for the linking of environmental issues and economics.

Arthur's (2013) Complexity Economics is relevant with 450 citations. Furthermore, his recent (2021) article in Nature Review Physics. This already has 85 hits. Arthur is documented as being one of the first economists to be substantially involved with the Santa Fe Institute and this involvement has continued for several decades (Fontana 2010). An examination of Arthur's own Google Scholar credentials reveal that he has 50,315 citations. Arthur challenges the basis of neoclassical economics. He rejects the dominant idea of an equilibrium where markets are clear to balance demand and supply. Instead, he argues that consumer and agent behaviour is diverse and evolving, leading to the emergence of new and novel aggregate outcomes. Therefore, economic interactions are not homogeneous but heterogeneous across a range of social networks. This often requires new and different mathematical approaches in economics. For policy makers, this means that they search for plausible patterns of interest that are limited in time and space rather than determined by universal laws. Policy makers face 'decision making under fundamental uncertainty' (Arthur 2021, p. 143).

In addition to an interest in the concept of 'emergence', Arthur is particularly influenced by several other concepts from complexity science such as: self-organisation (for explaining diversity within networks), power laws and long tails (for changing how policy makers and economists understand risk), and attractors (for explaining where specific empirical data patterns become important for a given time and space). With regard to methodology, Arthur focuses on consumer and agent behaviour in social networks and notes the importance of agent-based modelling as an excellent computation tool for modelling degrees of diversity in patterns of emergent behaviour in a given market context. Like almost all complexity theorists and practitioners in economics, he is committed to interdisciplinarity across the sciences and social sciences and is concerned if economics operates as a discipline in isolation from others.

Other notable substantial contributions identified in the Google Scholar search include Durlauf with two papers that are highly cited (Durlauf 2005, 2012) with 116 and 264 citations. His paper (2012) in Politics, Philosophy and Economics argues that complexity thinking adds value to contemporary economic modelling and analysis, but that it is not a theoretical paradigm shift, and he doubts the real benefits for public policy evaluation. He argues for a greater clarity about the mathematical tools that complexity theory provides for economic analysis. In the earlier paper (2005) published in The Economic Journal, he defines the empirical methods most used by complexity economists as: historical studies, power laws, and analyses of social interactions. He expresses scepticism about the extent to which the use of these methods validates the properties of complex systems.

Another scholar with substantial relevant citations is Rosser with 6660 citations on his Google Scholar author page. His most cited article (581 citations) of direct relevance is a paper in The Journal of Economic Perspectives (Rosser 1999). He argues that complexity economics have evolved from previous approaches examining cybernetic, catastrophic, and chaotic systems. Economic agents are dispersed and adapt their learning and novelty. Rationality becomes bounded. System simulation becomes an important method to understand complexity.

Rosser has also published with two other well cited authors (Holt et al. 2011). Their review of the state of the art of complexity and economics has 172 citations. Neither have Google Scholar author summary web pages, but both have other books and articles listed. For example, Colander's (2000) single authored book: Complexity and the history of economic thought, is cited 109 times.

Antonelli (2008, 2009) has two single authored papers both with substantial numbers of citations (363, in 2008, and 159, in 2009). He is professor of Economics at the University of Torino and has 12,842 citations on Google Scholar. His scholarship is specific to the economics of technological innovation. He explores and explains innovation as a path-dependent process rooted in the interdependence and interaction of a diversity of heterogeneous agents. He argues: location is important (relative to other agents), agent knowledge of others is always limited (so, none has complete knowledge), interaction is often localised, agents are creative and can deviate from given rules, but agents are also highly interdependent causing systemic phenomena.

It is important to conclude at this point that using Google Scholar in this way is exploratory and not as rigorous and focused as imposing systematic boundaries as used later in this article by applying the PRIMSA method. Nevertheless, it allows for illustration of some of the most important historical influences. The worst consequence is the exclusion of important publications that are very closely related to the topic of interest, but which use title labels that are different.

A good example, offered by one of the reviewers of this paper is when "complexity" is substituted with "evolutionary". Evolutionary economics is another subject having high impact on the discipline and with much overlap with complexity theory. A specific example is the work of Jason Potts. His Google Scholar author home page has 11,411 citations with several highly cited publications that include the keyword "evolutionary" in the title. On examination, the content overlaps with the conceptual domain of complexity economics. For example, his book: The New Evolutionary Microeconomics (2000) has 868 citations.

Similarly, peer reviewers of our article have pointed out that the eminent international scholar Doyne Farmer, Professor of Mathematics and Director of Complexity Economics at the University of Oxford, does not feature in our Google Scholar summary results, but he has highly cited articles that include the title keywords "chaos" and "chaotic". In total he has 41,215 citations and one of his most highly cited articles is relevant to complexity and economics: 'Predicting chaotic time series' (Farmer and Sidorowich 1987) published with Sidorowich. It is cited 2782 times. These two examples illustrate the limits of using Google Scholar to acquire an overview.

This first overview search with Google Scholar provides a coherent but imperfect sense of the theoretical and conceptual framework of complexity theory as applied to economics.

3.2. Systematic Literature Review

Given what was identified in the broad Google Scholar search about conceptual priorities of complexity theory for economics, our thematic analysis of the PRISMA selected articles focused first on identifying the key conceptual issues presented by each selected publication, and how these compared with each other. Next, we identify the main methodological frameworks used by each publication, placing them into groups of similarity and difference in this respect. Finally, we examined the application of the research and scholarship in the context of the traditional coverage of economics: Macro, Meso and Micro.

3.2.1. Complexity Themes

A central theme emerging across the studies included is the fact that complex systems demonstrate multiple properties (Cilliers 1998). For this reason, in our thematic analysis, we identify a central focus on specific complexity themes across the publications included. While there are overlaps, the majority of studies considered in our analysis discuss non-linearity (43), adaptation (16), system interactions (49) and resilience (5). Table 2 provides an overview of the dominant complexity properties discussed across the 113 publications.

Table 2. Emergent Complexity Properties.

Complexity Themes	Publications	Total
System Interactions	Aeeni and Saeedikiya (2019); Ahmad (2019); Albin and Foley (2001); Aouad and Bento (2019); Bianchi and Labory (2019); Brocal et al. (2019); Bruno et al. (2018); Budd et al. (2017); Chakraborti et al. (2021); Chikumbo et al. (2000); Çıdık and Phillips (2021); Coyne et al. (2021); Dong and Fisher (2019); Evans et al. (2017); Forbes and Xie (2018); Garmendia and Stagl (2010); Georgiev et al. (2015); Gimzauskiene and Kloviene (2010, 2011); Guo et al. (2021); Hartwell (2019); Jemmali (2022); Korotkikh and Korotkikh (2009); Kopp and Salecker (2020); Lamghari Elidrissi et al. (2020); Liu et al. (2021); Markose (2005); Marle (2020); Matesanz Gomez et al. (2017); Millhiser and Solow (2007); Mylek and Schirmer (2020); Naderpajouh and Hastak (2014); Oughton et al. (2018); Patrucco (2011); Phillips (2019); Qiu-Xiang et al. (2018); Ryan et al. (2007); Stuart et al. (2022); Tang and Gao (2014); Vallance (2016); Varga et al. (2016); Watson et al. (2011); Watson et al. (2011); Wheeler (2007); Wink et al. (2017); Xepapadeas (2010); Zhang et al. (2021b); Zheng and Chen (2012); Zhu et al. (2017);	49
Non-linearity	Aldhyani et al. (2021); Aymanns et al. (2018); Balint et al. (2017); Batabyal and Beladi (2011); Berg et al. (2002); Brunk and Hunter (2008); Chae (2012); Cioffi-Revilla (2014); Colander et al. (2010); Cooper (2011); Dai (2021); Dosi and Roventini (2017); Elsner (2017); Espejo (2018); Friedrich et al. (2021); Gaffeo and Tamborini (2011); Garmendia and Gamboa (2012); Gligor et al. (2022); González-Velasco et al. (2019); Green and Newth (2001); Hausner et al. (2021); Hommes (2006); Kirman (2010); Kukacka and Kristoufek (2020); Lee and Kim (2018); Li et al. (2020); Majeed and Shah (2015); May et al. (2011); Monasterolo et al. (2019); Mueller (2020); Oldham (2020); Raimbault (2019); Rammel et al. (2007); Rutkauskas et al. (2014); Shen (2021); Sitthiyot (2019); Stahel (2006); Stauffer et al. (2022); Sun and Zhong (2020); Tesfatsion (2006); Villani et al. (2018); Yaneer (2004); Zhang et al. (2021a);	43
Adaptation	Adamides and Pomonis (2009); Aldunate et al. (2005); Bento and Garotti (2019); Braz and de Mello (2022); Corbacioglu and Kapucu (2006); Garver (2019); Kim and Mackey (2014); Kukacka and Kristoufek (2021); Li et al. (2010); Maswana (2009); Matutinović (2001); Milne (2009); Sfa et al. (2020); Shobe (2020); Wiesner and Ladyman (2021); Zhang and Cui (2016)	16
Resilience	Darnhofer (2014); Fraccascia et al. (2018); Korhonen and Snäkin (2015); Plummer and Armitage (2007); Shachak and Boeken (2010);	5
Grand Total		113

In complexity thinking, systems exhibit non-linear effects and as such they behave in ways that the effects of inputs may not be proportional to outcomes (Beinhocker 2006). From this perspective, slight changes to conditions (initial or in the external environment) can result in larger unpredictable consequences (Turner and Baker 2019). In this realm, systems operate in an unpredictable manner (Hanseth and Lyytinen 2016), reacting disproportionately to their environment (Turner and Baker 2019). For publications that focus on non-linearity, these studies attempt to develop and conceptualise social reality from a Complex Adaptive Systems (CAS) viewpoint, although placing emphasis on the non-linear nature of these systems or their external environment. For example, Gligor et al. (2022) apply this perspective in their observation of gender differences in logistical innovations. Touching on other concepts such as emergence and multiple causality, these scholars highlight how diversity in innovation teams and workforce provides a deeper understanding to customer needs. Their research also shows how applying complexity appropriate methods such as QCA can provide insights that other mainstream 'regression-based' approaches may be unable to. Taking an evolutionary approach, Chae (2012) also applies complexity theory to demonstrate predictability, localization, and emergence in service innovation. Importantly, Chae (2012) notes that the environment of service innovation is multifaceted, and uncertain.

Monasterolo et al. (2019) argue that traditional economic and financial risk models do not offer the capacity needed to develop appropriate climate risks models and climate-alignment opportunities. For these authors, this is due to the constrains of 'equilibrium conditions and linearity of impacts, as well as by representative agents and intertemporal optimization' (Monasterolo et al. 2019, p. 177). Instead, they attempt to fill this gap by advocating the use of complexity appropriate methods, such as agent-based and network models, for effective alignment between national and global climate targets. Supporting this, Balint et al. (2017) also argue that decentralised economic models offer alternatives to equilibrium-based models in their assessment of non-linear effects. Batabyal and Beladi (2011) take a similar non-equilibrium view in their assessment of agricultural resilience. These scholars also note a need for a departure from equilibrium-based approaches. From these studies, it is evident that the influence of complexity theory has resulted in a different worldview. This particular set of complexity thinkers demonstrate ways to identify and tackle non-linearity across complex systems. The particular focus on the area of ecological economics highlights the need for more realist assessment of policy impacts within this area. Nevertheless, publications within this cluster are premised on the notion that the social world operates in in an unstable and non-predictable uncertain manner. This highlights the need for new ontological and methodological frameworks that transcends the reductionist paradigm.

Our thematic analysis also identified 49 publications (Table 2) that attempt to capture the interactions between and across systems from a multidimensional perspective. These publications provide demonstrations on how individual components of a system affect each other, and in some cases, influence actions. Xepapadeas (2010) advocates the need for adequate modelling that looks at spatial interactions induced by feedback. He finds that linear dynamics are not adequate illustrations of ecological systems. Gimzauskiene and Kloviene (2010, 2011) provide two publications that focus on the application of complexity theory in performance measurement systems. Here, they show an understanding of how systems interact with, and react to, the external environment. Applying complexity theory to the management of building construction projects, both Naderpajouh and Hastak (2014) and Çıdık and Phillips (2021) emphasise the importance of social interactions on risk management. Zhu et al. (2017) provide a unique demonstration of levers and hubs, that is, when a component of a system has disproportionate influence over the whole due to structure and connections. Here, they attempt to develop a model that can predict degrading components. Mylek and Schirmer (2020) also provide an application of complexity thinking in communication strategies. They develop an approach to the design of communication, with the intent to match the complexity of the information with the population. Zhang et al.

(2021b) show how institutional complexity can be applied with paradox theory to aid in efficient industrial change management, especially when faced with paradoxicalities.

In so far as systems operate in a non-static dynamic manner, and interact with each other, their components tend to adapt to, or learn from, changes to their environment. Sixteen publications (Table 2) also focus on adaptation, these studies provide a diversity of theoretical and contextual applications within which a system is seen to generate adaptive capabilities. Corbacioglu and Kapucu (2006), Li et al. (2010), Adamides and Pomonis (2009) and Zhang and Cui (2016) apply complexity theory to management practices and show how their attributes spontaneously adapt to changes in the environment. Here, adaptation may stem from organisational learning and self-adaptation in for instance, dynamic disaster environments (Corbacioglu and Kapucu 2006) or interactions within the external environment (Adamides and Pomonis 2009). Zhang and Cui (2016) attempt to quantitatively describe how a complex adaptive system highlightssystems self-adaptive to changing environments while Li et al. (2010) attempts to develop a multi-agent model that also factors in path dependency. Kim and Mackey (2014) and Garver (2019) also demonstrate how the environmental legal system can be viewed as adapting to its environment and suggest a systems-based assessment methodological viewpoint. Studies within this thematic cluster demonstrate how adaption may emerge when systems are at tipping points (Shobe 2020) or on the edge of chaos and uncertainty (Kim and Mackey 2014).

Finally, five articles (Table 2) major on the concept of resilience within the context of complexity theory. These publications take a more ecological perspective in their application of complexity theory. Darnhofer (2014) sees resilience as how complexity theory views the economic world as fundamentally unpredictable and actors and organisations must adapt to face this unpredictability. Korhonen and Snäkin (2015) examine resilience alongside efficiency and see resilience as achieved through diversity of resources. Plummer and Armitage (2007) and Shachak and Boeken (2010) take a non-equilibrium viewpoint in their development of an evaluation frameworks for ecological co-management. These authors argue that interactions do not always produce linear outcomes but are important for social-ecological resilience. Using a bibliometric analysis, Fraccascia et al. (2018) provide a comparison research study in ecological studies focusing on resilience. They show the multidisciplinary nature of resilience, especially in the fields of environmental science, ecology, and engineering.

3.2.2. Methodology and Method

Table 3 shows the overall comparison of the dominant methodology approach to research design across the 113 publications. The largest frequency is for those 45 publications that use a quantitative design. There is a variety of quantitative designs including: multi-agent and agent based modelling (Kukacka and Kristoufek 2020; Li et al. 2010; Hommes 2006; Tesfatsion 2006); Scenario Analysis (Korhonen and Snäkin 2015); Risk Assessment (Naderpajouh and Hastak 2014); Real Option Analysis (ROA) (Guo et al. 2021); statistical analysis of empirical data (Mylek and Schirmer 2020; Kijazi and Kant 2013; Gimzauskiene and Kloviene 2010, 2011); Intelligent Algorithms (Jemmali 2022); Power Law Distributions (Phillips 2019); modelling of live and empirical data (Zhu et al. 2017); and a NK model of fitness landscapes (Adamides and Pomonis 2009).

Table 3. Frequency of Overall Method in the Research Design.

Methodological Approach	Publications	Total
Quantitative	Adamides and Pomonis (2009); Aldhyani et al. (2021); Aymanns et al. (2018); Chakraborti et al. (2021); Chikumbo et al. (2000); Evans et al. (2017); Forbes and Xie (2018); Friedrich et al. (2021); Gimzauskiene and Kloviene (2010, 2011); González-Velasco et al. (2019); Guo et al. (2021); Hartwell (2019); Hommes (2006); Jemmali (2022); Kopp and Salecker (2020); Korhonen and Snäkin (2015); Korotkikh and Korotkikh (2009); Kukacka and Kristoufek (2021); Kukacka and Kristoufek (2020); Lamghari Elidrissi et al. (2020); Lee and Kim (2018); Li et al. (2010); Maswana (2009); Matesanz Gomez et al. (2017); Millhiser and Solow (2007); Mylek and Schirmer (2020); Naderpajouh and Hastak (2014); Oldham (2020); Phillips (2019); Qiu-Xiang et al. (2018); Rutkauskas et al. (2014); Shachak and Boeken (2010); Shen (2021); Sitthiyot (2019); Stauffer et al. (2022); Tang and Gao (2014); Tesfatsion (2006); Watson et al. (2011); Xepapadeas (2010); Zhang and Cui (2016); Zheng and Chen (2012); Zhu et al. (2017); Villani et al. (2018); Zhang et al. (2021a)	45
Case study and/or systems model	Ahmad (2019); Albin and Foley (2001); Aldunate et al. (2005); Aouad and Bento (2019); Batabyal and Beladi (2011); Bento and Garotti (2019); Berg et al. (2002); Bianchi and Labory (2019); Braz and de Mello (2022); Brunk and Hunter (2008); Budd et al. (2017); Chae (2012); Cioffi-Revilla (2014); Darnhofer (2014); Dong and Fisher (2019); Dosi and Roventini (2017); Espejo (2018); Garmendia and Stagl (2010); Garver (2019); Kim and Mackey (2014); Liu et al. (2021); Matutinović (2001); Oughton et al. (2018); Patrucco (2011); Plummer and Armitage (2007); Ryan et al. (2007); Sfa et al. (2020); Shobe (2020); Stuart et al. (2022); Vallance (2016); Varga et al. (2016); Watson et al. (2011); Markose (2005); Yaneer (2004); May et al. (2011); Marle (2020); Brocal et al. (2019); Wheeler (2007); Raimbault (2019); Li et al. (2020); Dai (2021); Sun and Zhong (2020)	42
Qualitative	Bruno et al. (2018); Çıdık and Phillips (2021); Coyne et al. (2021); Elsner (2017); Georgiev et al. (2015); Hausner et al. (2021); Kirman (2010); Milne (2009); Mueller (2020); Stahel (2006); Wiesner and Ladyman (2021)	11
Literature Review	Aeeni and Saeedikiya (2019); Balint et al. (2017); Colander et al. (2010); Cooper (2011); Gaffeo and Tamborini (2011); Green and Newth (2001); Majeed and Shah (2015); Monasterolo et al. (2019); Rammel et al. (2007)	9
Mixed Methods	Corbacioglu and Kapucu (2006); Garmendia and Gamboa (2012); Gligor et al. (2022); Wink et al. (2017)	4
Systematic Literature Review	Fraccascia et al. (2018); Zhang et al. (2021b)	2
Grand Total		113

These examples show the use of quantitative methods to model complexity are diverse, ranging from theoretical mathematical modelling of what a complex economic system might be like, to empirical based models that use historical or current data collections. The quantitative designs explore research questions both for macroeconomics and microeconomics. Furthermore, it is clear in the systematic review that complexity theorists often try to include aspects of the interaction of macro and microeconomics, and the interface between them. This mid-level interaction is referred to in this article as 'meso economics'. The quantitative microeconomics research that is identified includes applications for financial markets, manufacturing, production, engineering, construction, and environmental concerns.

There are four mixed methods publications in Table 3 and these include the mathematical approaches of Qualitative Comparative Analysis (QCA) (Gligor et al. 2022) and Cluster Analysis (Garmendia and Gamboa 2012). This is interesting given that these are case based methods widely advocated for exploring and explaining complexity in the political sciences and sociology (Rihoux and Ragin 2009). Case based methods are regarded as appropriate in these disciplines because of their ability to detect different causal configurations that evidence social complexity (Haynes 2018). Corbacioglu and Kapucu (2006) used mixed methods to compare the economic adaptation of communities in disasters in Turkey.

Forty-two publications included in our systematic review are best described methodologically as case studies and/or system models. This combined category is because the case studies about complexity theory are not mutually exclusive from system models, which also often use real world examples to embed their concepts. However, some of these articles did this case example embedding much more than others. Some of the system models were primarily case studies and then analysed as system models, while other articles set out much more to define approaches to system modelling and perhaps only included a limited and generalised real-world example. An example of theoretical system modelling is Plummer and Armitage's (2007) model of adaptive co-management of resources in a complex environment.

Garver's (2019) publication in Ecological Economics is recognisable as a form of economic discourse, and it takes an abstract theoretical approach to the ambitious topic of the global economic system. The article examines the economy in relation to the interventions of the law and governance and how these macro entities interact through leverage points and lock-ins. If there is a case study in this article, it is the global system. This system modelling approach has some similarities to Kim and Mackey's (2014 synthesis of international law as a complex adaptive system).

In contrast, the publications by Darnhofer (2014) and Braz and de Mello (2022) develop system models that are much more explicitly embedded in real world case studies. Darnhofer focuses on farm management as a definable system, but not a specific farm, or farming community in time and space. Braz and de Mello use the case study of a well specified supply chain economy in Brazil, using 'within' and 'across' case analysis. This case analysis clearly aids the explanation and conceptualisation of their theoretical model.

There were two previous systematic literature reviews discovered in our systematic review. Zhang et al. (2021b) explore complex 'paradoxes' in supply chain management, for example, improving inventory levels for operational flexibility and effectiveness, but whilst reducing inventory costs. Their article therefore sought out previous research on a very discrete subtopic on the periphery of mainstream complexity theory and was unlike the theoretical coverage of many (but not all) of the publications in our review. In other words, it is found that many of the articles attempted the opposite approach to Zhang et al. (2021b), preferring to offer ambitious and broad coverages across the metatheoretical landscape of complexity theory, rather than understanding a discrete sub-concept such as paradox. The narrow focus of their systematic review is a methodology strength in our opinion. Fraccascia et al. (2018) examine what they describe as 'state of the art' literature on complex systems and resilience and argue the literature is interdisciplinary but lacking in a shared understanding of a definition of resilience as a concept. They use a novel cross citation network analysis of the literature identified.

Nine other articles listed in our review were primarily unsystematic literature reviews. These publications deliberately use the research design of focusing on a controversial or seminal set, or single piece, of literature about the application of complexity to economics. The authors seek to add some original points to these arguments. Sometimes these designs are related to interdisciplinary theoretical areas. For example, Monasterolo et al. (2019) use some existing literature to argue for the need for a more robust approach to integrating macroeconomics models with an ecological perspective. Levanti (2018) looks at specific aspects of leading macroeconomic policy in complex socio-economic networks. While these two papers are in danger of presenting a rather esoteric contribution to the metatheoretical challenges of applying complexity theory, in contrast, Balint et al. (2017) present a well-structured critique of the literature on key areas of methodology. They focus on some literature covering the use of agent-based, network, and system dynamics models in ecological economics. While an obvious critique is that this is not done using a systematic method, the paper nevertheless gives a well-structured and robust account of methods that our own systematic review here also evidences as core territory to the application of complexity theory to economics. As a result, on page 262, Table 1, they provide a convincing summary of a comparison of system dynamics models and agent-based models with traditional equilibrium-based models. In their conclusion, they add weight to the prevailing direction of methodological changes in the sphere of applying complexity theory to economics:

' ... agent-based models are increasingly considered as a prominent alternative to standard general equilibrium models which overlook many of the risks of climate change.' (Op cit, 262)

In another of the identified articles, Holt et al. (2011) draw primarily on existing writings rather than data and modelling to progress scholarship. They make an explicit and unapologetic contribution to an ongoing debate in the literature about whether complexity economics is really mainstream or heterodox. They argue that heterodox economics, especially when exploring scientific theories such as complexity, is not heterodox, but rather a necessary evolving of the mainstream discipline.

Finally, there are 11 articles in Table 3 using qualitative research methods. The definition of 'qualitative' here is broad and includes publications that discuss and argue conceptual issues, without being founded on specific literature or literature searches. For example, Kirman (2010) argues the weaknesses of General Equilibrium Theory and its impact on financial modelling and sees a complex adaptive systems approach as needed to better forecast major economic change. Coyne et al. (2021) look at conceptual issues and challenges in the interdisciplinary domain that overlaps public health with economics.

Çıdık and Phillips (2021) collect empirical qualitative data and analyse it for the journal Construction Management and Economics. They combine complexity theories with organisational approaches to reliable organisations to understand the impact of organisational culture on building safety. This is an alternative to taking a reductionist and quantitative approach to risk that assumes organisational stability over time. Twelve unstructured interviews are used to obtain evidence from experts. Social interaction is viewed as an important aspect in mitigating risk, this in addition to classical approaches to quantitative assessments of materials and costs associated with risks of combustibility.

3.2.3. Applications and Impact

Table 4 shows the frequencies of the type of application in economics contributed by the publications reviewed. This is on the basis of a division into the categories: macro, meso and micro.

Table 4. Summary of the Publication Applications.

Summary Type of Application	Publications	Total
Macro	Aymanns et al. (2018); Balint et al. (2017); Bianchi and Labory (2019); Brunk and Hunter (2008); Bruno et al. (2018); Chikumbo et al. (2000); Colander et al. (2010); Cooper (2011); Darnhofer (2014); Dosi and Roventini (2017); Elsner (2017); Espejo (2018); Evans et al. (2017); Forbes and Xie (2018); Friedrich et al. (2021); Gaffeo and Tamborini (2011); Garver (2019); González-Velasco et al. (2019); Green and Newth (2001); Kim and Mackey (2014); Kirman (2010); Kukacka and Kristoufek (2020); Lee and Kim (2018); Maswana (2009); Matesanz Gomez et al. (2017); Matutinović (2001); Milne (2009); Monasterolo et al. (2019); Mueller (2020); Plummer and Armitage (2007); Ryan et al. (2007); Sitthiyot (2019); Stauffer et al. (2022); Tang and Gao (2014); Wiesner and Ladyman (2021); Xepapadeas (2010); Zheng and Chen (2012); Watson et al. (2011); Markose (2005); Yaneer (2004); Villani et al. (2018); Fraccascia et al. (2018); Raimbault (2019); Li et al. (2020); Sun and Zhong (2020)	45
Meso	Adamides and Pomonis (2009); Aeeni and Saeedikiya (2019); Ahmad (2019); Batabyal and Beladi (2011); Braz and de Mello (2022); Budd et al. (2017); Chae (2012); Chakraborti et al. (2021); Cioffi-Revilla (2014); Corbacioglu and Kapucu (2006); Coyne et al. (2021); Garmendia and Gamboa (2012); Garmendia and Stagl (2010); Georgiev et al. (2015); Gimzauskiene and Kloviene (2010, 2011); Hartwell (2019); Hausner et al. (2021); Hommes (2006); Korhonen and Snäkin (2015); Korotkikh and Korotkikh (2009); Kukacka and Kristoufek (2021); Li et al. (2010); Millhiser and Solow (2007); Oldham (2020); Patrucco (2011); Phillips (2019); Qiu-Xiang et al. (2018); Rammel et al. (2007); Rutkauskas et al. (2014); Shachak and Boeken (2010); Shobe (2020); Stahel (2006); Stuart et al. (2022); Tesfatsion (2006); Wink et al. (2017); Zhang and Cui (2016); Zhang et al. (2021a); Dai (2021)	39
Micro	Albin and Foley (2001); Aldunate et al. (2005); Aouad and Bento (2019); Bento and Garotti (2019); Berg et al. (2002); Çıdık and Phillips (2021); Dong and Fisher (2019); Gligor et al. (2022); Guo et al. (2021); Jemmali (2022); Kopp and Salecker (2020); Lamghari Elidrissi et al. (2020); Liu et al. (2021); Majeed and Shah (2015); Mylek and Schirmer (2020); Naderpajouh and Hastak (2014); Oughton et al. (2018); Sfa et al. (2020); Shen (2021); Vallance (2016); Varga et al. (2016); Watson et al. (2011); Zhu et al. (2017); May et al. (2011); Marle (2020); Zhang et al. (2021b); Brocal et al. (2019); Aldhyani et al. (2021); Wheeler (2007)	29
Grand Total		113

Macroeconomics counts applications that are primarily directed at national and global economic issues. Microeconomic applications count applications that are primarily concerned with specific organisations and how individual agent behaviour contributes to collective phenomena. Meso economics is focused on the interaction of micro elements with macro elements and how the two dimensions influence and change each other. For example, from the publications considered in our systematic review, Li et al. (2010) see the disruption and uncertainties that external influences have on local organisational processes and systems.

The frequencies of the trio of macro, meso, micro groupings for the publications considered are relatively evenly distributed (Table 4). The importance of meso considerations (n = 39) shows that complex systems theoretical frameworks can be expected to lead researchers towards the interface between individual agents with their locality and the associated relational connections they have with regions, nations, and globalisation. Examples of this from the meso publications we review, include Shobe's (2020) critique of the difficulty with applying an optimal policy process to the decentralisation of environmental policy making due to the tightly connected and interlinking of organisations and devolved political geographies who have a stake in outcomes. Shobe sees studies of linked and adaptive complex systems as a key methodology for improving policy applications.

Zhang et al. (2021b) acknowledge the paradoxes and contradictions within patterns of agent interactions and how they make sense of the world. This is an aspect of complex outcomes that needs acknowledgment in applications to management practice. Korhonen and Snäkin's (2015) approach to modelling the Finnish energy system argues it is important to research the interdependent aspect of systems and their boundaries, thereby examining a specific city in relation to other municipalities with which it is regionally linked. Such a quantitative model evidences the importance of collaboration between cities and regions. Similarly, but applying a case study approach rather than a quantitative model, Braz and de Mello (2022) propose a meso complexity informed systems framework that includes management mechanisms, in addition to attributes of the internal and external environment.

Patrucco (2011) describes how changes in the network of the automobile production system in northern Italy is sustained by the dynamic interactions between firms. This modifies the behaviour of the key economic actors involved and promotes cross sector innovation and change with macro consequences. Furthermore, Gimzauskiene and Kloviene (2011), argue for an integrated meso approach to performance management that includes both internal and external influences for any individual organisation. Complexity, as uncertainty in the operating environment, becomes a key component of adaptive performance management (Gimzauskiene and Kloviene 2010). Likewise Batabyal and Beladi (2011) argue the multiple influences on range management in farming.

Garmendia and Gamboa's (2012) seek to model the many interests of different social groups towards sustainable natural resource management in northern Spain. They evidence that patterns of actor priorities can be grouped rather than being unrelated, but more importantly can give feedback into the dynamics of higher-level deliberation about social and economic change.

A model of service innovation developed by Chae (2012, p. 820) provides evidence of the meso dimensions that impact change in the service industry.

'Services arise and are emergent through recombination and/or reconfiguration of diverse resources and contexts from service provider, customer, and other economic actors. This recombinant/reconfiguring process, along with an effective balance of mutation and crossover, is a key for business growth and customer service experience.'

Garmendia and Stagl (2010) examine the interaction of participation about sustainability with the need to change social views and attitudes to ecology and economics. They conclude that there are uncertainties about participatory approaches to changing public attitudes towards the economics of sustainability.

These sorts of ambitious attempts at modelling the meso complexity and uncertainty of interactive agents and systems raises the issue about how useful such models can be for applied operational management applications, and whether the research outcomes offer only broad advice, such as the need for a good external view of economic and social change, and the ability to adapt policy and decisions rapidly in response.

Nevertheless, Adamides and Pomonis (2009) argue the emergence of new forms of organisational order from this complex and unpredictable range of meso influences. Rammel et al. (2007) assert the importance of a conceptual approach that understands non-linearity, non-equilibrium, and the resulting co-evolution of the system, if any progress is to be made in a research agenda that informs resource management. For Tesfatsion (2006) and Hommes (2006) ABM and its advancement through related dynamic methods is the research design of choice for progressing research on these meso-economic approaches. Phillips (2019) is concerned with the real-world example of bankers and financiers at the micro level misunderstanding risk with adverse consequences for macroeconomic policy, as in the Great Financial Crisis of 2008. Power Law distributions are seen as the research solution for getting better decision making that avoids such risks in the future.

Given that complexity focused approaches to solving meso-economic challenges are conceptually and methodologically ambitious, and offer limited insights to 'wicked' problems, it is not surprising that some applications identified in the selected publications reviewed still use either a macro or micro approach. Here, the system boundaries are restricted to either the global geopolitical economic system, often in the form of ecological economics, or the detail of production or performance within a single organisational system.

Of the 45 publications identified in Table 4 as having macro applications, five of these are published in the journal Ecological Economics. Monasterolo et al. (2019) argue for the changes in economic modelling necessary if countries are to hit global climate targets. Complexity science and evolutionary economics are seen as providing the fundamental framework for these changes. Garver (2019) argues for law and governance system changes in order to make global ecological improvements and identifies system leverage points to achieve change. Balint et al. (2017) cite both micro and macroeconomic literature, but produce largely macroeconomic conclusions about the importance of complexity economics models to provide knowledge on coalition formation, the macroeconomic impact of climate change, energy market dynamics, and the uptake of sustainable technologies. An earlier article by Plummer and Armitage (2007) provides an evaluative framework for the adoption of macro ecosystem and livelihood conditions, alongside the necessary governance changes. Matutinović (2001) hypothesises that socio-economic diversity is a prerequisite for social and ecological stability. At the core of these articles published in Ecological Economics is a meta world view of economics embedded with other global systems such as the available physical resources, climate dynamics and population demographics.

The other publications classified as being applied to macroeconomics in Table 4 include two in sources covering agricultural economics. Xepapadeas (2010) argues for a complexity approach to modelling that includes: nonlinear feedbacks, and spatial and temporal aspects. Darnhofer (2014) develops the concept of resilience as an alternative to equilibrium. This is a method for substantiating both complex system dynamics and the role of individual farms in managing macro social and ecological change. Farms are resilient to external changes by having a buffer capability, and an adaptive and transformative capability.

Other articles classified in Table 4 as having a macroeconomic approach include one about the importance of legal governance within a global economic system (Kim and Mackey 2014). Another by Holt et al. (2011) in Post Keynesian Economics argues that complexity economics needs a broad view of what is accepted within the economics discipline, rather than recognizing alternatives to classicism as heterodoxy. Furthermore, Brunk and Hunter (2008) offer an ecological approach to economic stagnation. They conclude that traditional macroeconomic policy approaches will exacerbate economic problems. Mueller (2020) concludes on the inevitable risk of policy failure for much macroeconomic intervention into complex global and national systems. Matesanz Gomez et al. (2017) argue the great financial crisis of 2008 resulted in increased macroeconomic system changes in Europe that challenge the commonly accepted notion of identifiable core and peripheral euro zone countries. Gaffeo and Tamborini (2011) examine the challenge of regulating macroeconomic finance in an age of globalisation and open capital markets. They see the usefulness of network theory and approaches but conclude that major questions remain about how to apply such idea to regulatory policy interventions. Milne (2009) examines the aims of macroprudential policy and concludes the most important aspect is to maintain the flow of finance through the economic system.

Twenty-nine publications are classified in Table 4 as being primarily micro in their complexity economics design. Jemmali (2022) creates a smart car parking system that enables a health service to vaccinate the most efficient number of people with a given period of time and resources. Gligor et al. (2022) research gender differences in logistics innovation. They identify different causal configurations for innovation with important gender differences across these configurations.

Several publications focus on novel approaches to understanding risk. Brocal et al. (2019) critique current models of risk management and propose a complex system of governance for better risk management. Çıdık and Phillips (2021) research professional opinions about high-risk buildings and conclude that collective culture as social interaction is an important aspect for reducing risk in addition to structured interventions for assessing physical conditions. Mylek and Schirmer (2020) measure the extent to which public actors have some degree of cognitive complexity as 'integrated complexity' in their ability to comprehend the socio-economic trade-offs, if policy interventions are to reduce wildfire risks. Another study that brings advances in complexity theory to agent perspectives and how they interact dynamically, is Naderpajouh and Hastak's (2014) concept of Interaction Analysis (IA). This forms a new type of risk assessment that estimates newly emerging risks in major construction projects.

Other microeconomic publications informed by complexity economics also examine uncertain outcomes from agent activities. Guo et al.'s (2021) model theorises how to optimise concessions to suppliers. This is during the unstable context of managing an ongoing public-private partnership contract. Kopp and Salecker (2020) look at how traders interact with their neighbours. Sellers' decisions about a buyer are often influenced by debt obligations and past interactions, including similar experiences of education, and living in close proximity. Kijazi and Kant (2013) theorise an approach to complex agent behaviour as 'socially rational' agents. These types of analysis of complex agents takes economic perspectives far beyond the concept of rational economic agents who are assumed to behave in similar ways. Nevertheless, agents are influenced by complex patterns of behaviour, often influenced by similar cross cutting social networks.

Not all the micro focused publications examine human interaction and behaviour. Zhu et al. (2017) analyse physical inputs and processes, rather than human actors, this in an engineering production process. They develop a quantitative model to measure the likely boundaries of component degradation (condition-based maintenance) within a complex multifaceted engineering process.

4. Conclusions

Figure 2 shows the frequency of publications from our systematic review over time. This highlights the growing applications of complexity theory in economic research. The trend for the publications included in our systematic review also provides some interesting suggestions on the influence of the global environment and the importance of the contextualization of such events. For instance, the increase in publications during 2010 reflects the impacts of the financial crisis and a moment when academic scholarship further questioned the use of traditional 'linear' economic ontologies. There is also an increasing trend in relevant publications during the last 15 years, with some fluctuations in the most recent period after 2018. This may result because of publications taking their time to get listed on databases.

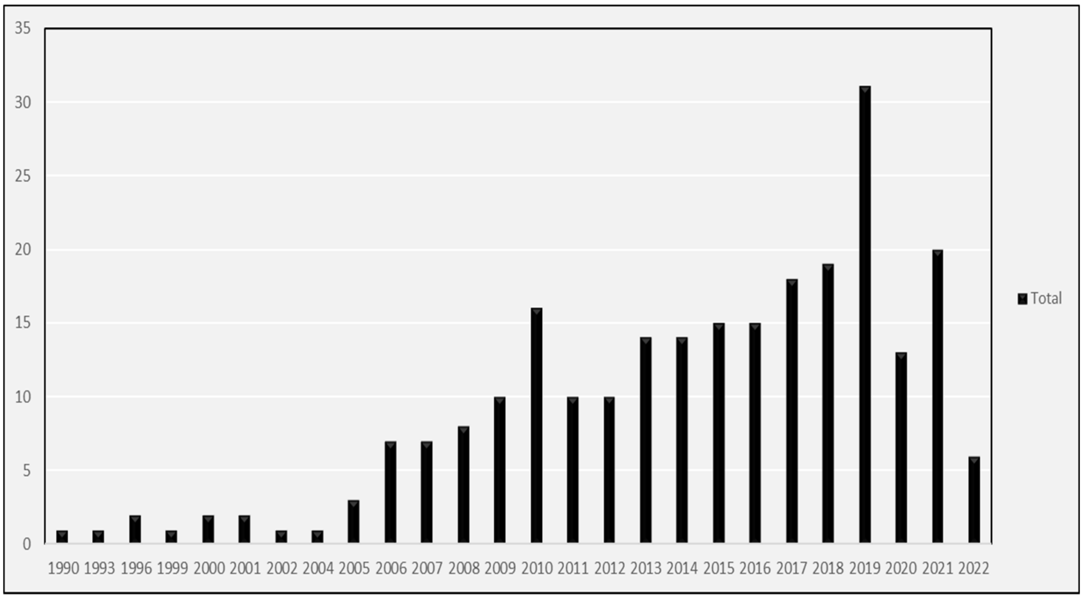

Figure 2. Frequency of Publications Over time.

Table 5 shows which of the reviewed publications have had the greatest impact through citations. The ratio index shows the annual ratio of citations per year, to avoid overly rating the impact of older articles. Hommes (2006) and Tesfatsion's (2006) contributions to the Handbook of Computational Economics have the highest ratios, an indication of the primacy that economics places on these kinds of contemporary quantitative models. Next, in Table 5 are a cluster of several authors publishing in the journal Ecological Economics, a journal that is clearly making an important impact in the integration of complexity theory with macro and meso system modelling that juxtaposes environmental and sustainability issues with the operations of governments and markets. This typifies the interdisciplinary approach of complexity economics. It is also an important observation given the current international concern about climate change and climate warming.

Table 5. Yearly ratio of citations—Top 15.

Rank	Author(s)	Year	Cited by	Ratio
1	Hommes	2006	576	33.88
2	Tesfatsion	2006	447	26.29
3	Plummer and Armitage	2007	346	21.63
4	Darnhofer	2014	161	17.89
5	Rammel, Stagl, and Wilfing	2007	228	14.25
6	Garmendia and Stagl	2010	175	13.46
7	Balint et al.,	2017	73	12.17
8	Fraccascia, Giannoccaro and Albino	2018	45	9.00
9	Kirman (2010)	2010	116	8.92
10	Coyne et al. (2021)	2021	16	8.00
11	Jemmali (2022)	2022	7	7.00
12	Garmendia and Gamboa (2012)	2012	72	6.55
13	Brocal et al. (2019)	2019	26	6.50
14	Zhang et al. (2021b)	2021	13	6.50
15	Kukacka and Kristoufek	2020	19	6.33

The interdisciplinary nature of complexity theory goes much wider than just this important single journal of Ecological Economics, and the different juxtapositions of other disciplines with economics is evidenced by the range of publication titles in Table 1. The nature of this interdisciplinarity is that it manifests itself especially in sub-disciplinary areas such as business and management studies, and ecology, rather than impacting the historical core of the foundation social science disciplines such as economics, sociology, and psychology. This leaves complexity economics open to the criticism that it is on the periphery of the single discipline. However, conversely the interdisciplinary approaches are contemporary and dealing with current real-world problems and applications. An example is Darnhofer's system model of farm management published in 2014 that deals with how farms can be resilient to ecological and economic change, and it has the fourth highest citation ratio in Table 5. Not all interdisciplinary complexity work is applied across the meso 'connect' and some highly cited scholars attempt an ambitious system world macro view especially when modelling global issues such as sustainability (Balint et al. 2017; Plummer and Armitage 2007).

In the publications reviewed there was a strong presence of ecology and climate change modelling that locate economics in a greater 'world/ecological/global system'. Table 1 evidences this with nine publications coming from Ecological Economics and seven from Ecological Complexity. (The later journal includes important global systems approaches but is less directly related to economics and the analysis of markets). Highly cited examples of the more economics focused approaches in Table 5 include Rammel et al. (2007) and Garmendia and Stagl (2010) and Garmendia and Gamboa (2012).

In terms of metatheory, complexity contributes a stinging critique of earlier economic approaches through its focus on unpredictability (Arthur 2013, 2021; Beinhocker 2006). Linked to this is a revision of economic agents who become not only consumers, but active actors politically, and motivated by a range of social aspects. Agents are therefore seen as heterogeneous and diverse, but with some consistent patterns of behaviour, often manifest in networks. They are not homogeneous. This has influenced the type of modelling that results (Hommes 2006; Tesfatsion 2006; Monasterolo et al. 2019; Balint et al. 2017).

This aspect of complexity, and the acknowledgement of multiple influences on dynamic economic systems, results in numerous publications having a strong ambition to develop meso models that have the potential to include both macroeconomics and microeconomics in some aspect. Here, there is a linking of the levels of analysis (Korhonen and Snäkin 2015; Garmendia and Stagl 2010; Chae 2012). However, this also results in a caution about how the theory is applied. Sometimes applications are speculative and based on general principles rather than offering prescriptive techniques. Good examples are the approaches towards the management of risk in sectors such as finance, engineering, and production (Chae 2012; Naderpajouh and Hastak 2014; Zhu et al. 2017).

Some important conclusions can be drawn about the use of methods in complexity economics. Agent based models and similar theoretical simulations of how a complex economy might behave are popular and often widely cited (Hommes 2006; Tesfatsion 2006). It is surprising that mixed methods and causal configurative methods do not feature more. The best example of such practices being a recent publication that includes Qualitative Comparative Analysis (Gligor et al. 2022). It is the experience of the authors of this systematic literature review that these types of contemporary complexity appropriate methods are used much more in political science, public policy and sociology. Furthermore, in the UK, they have made an important impact on the work of the HM Treasury (Bicket et al. 2020).

The use of general systems models in the tradition of the late Donella Meadows (2008) continue to have a wide use and impact in complexity economics, especially when concurrent with ecological issues (for example, Matutinović 2001; Garver 2019). This is again evidenced from the important impact of the journal Ecological Economics. System models that combine economics with environmental issues also span a wide range of publications including: Cambridge Journal of Regions, Economy and Society, Ecological Complexity, Forest Policy and Economics and The Economic Review of Agricultural Economics.

Overall, there are two key sets of publications that our systematic literature review exposed about complexity economics. On the one hand, there is the scholarship that explicitly addresses recognisable aspects of the contemporary agenda of the economics discipline. We have tended to focus on this literature in the examples used in the thematic analysis. The second area of literature is more implicit in its juxtaposition of complexity and economics, it being primarily concerned with the scientific development of complexity theory. In this second field of publications, the ambitious and wide coverage of complexity science across many disciplines, results in the continuing development of the broad theoretical perspective, but where the application to the working practice of economics is often weak. In our review we have chosen to highlight more the best working examples of the application of complexity science that in our opinion are having the greatest impact on the application and practice of economics. It is our argument that this continues to be an important development and one that will continue to change the nature of economics and its applications. The literature review provided gives evidence for our argument.

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Data Availability Statement: It is possible to reproduce the systematic literature review used in this article, as the search terms are included in full in the text.

Conflicts of Interest: The authors declare no conflict of interests.

Note

1 The resulting search string: (KEY ("complexity theory" OR "complex system" OR "complex adaptive system") AND SRCTITLE (econ* OR complex*) AND ABS (policy OR management OR organization OR finan*)) AND (LIMIT-TO (LANGUAGE, "English")).

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