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Linking complexity economics and systems thinking, with illustrative discussions of urban sustainability

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The expanding research of complexity economics has been signalling its preference for a formal quantitative investigation of diverse interactions between heterogeneous agents at the lower, micro-level resulting in emergent, realistic socioeconomic dynamics at the higher, macro-level. However, there is scarcity in research that explicitly links complexity perspectives in economics with the systems thinking literature, despite these being highly compatible, with strong connections and common historical traces. We aim to address this gap by exploring commonalities and differences between the two bodies of knowledge, seen particularly through an economics lens. We argue for a hybrid approach, in that agent-based complexity perspectives in economics could more closely connect to two main systems thinking attributes: a macroscopic approach to analytically capturing the complex dynamics of systems, and an inter-subjective interpretivist dimension, when investigating complex social-economic order. Illustrative discussions of city sustainability are provided, with an emphasis on decarbonisation and residential energy demand aspects.

Key words: Complexity economics, Systems thinking, Sustainability
JEL classifications: A13, B59, Q01

1. Introduction

Contemporary large-scale urban problems are often interlinked, circular, value-ridden, historical and contextual. Their unravelling generates a web of synergies and trade-offs, with multiple possible solutions, set within an uncertain landscape. City development may foster macroeconomic growth and welfare, but can also generate a host of inter-related sustainability challenges, such as climate change, persistent inequalities, unaffordable and inadequate housing, congestion and pollution. Moreover, cities and their economies are not merely adaptive in the biological sense, but creative,

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imaginative and aspirational. Entrepreneurial imagination can stimulate the creative combination of actual capital goods, give rise to new emergent properties and inject novelty in real market processes (Harper and Endres, 2012; Lewis, 2016). As Jane Jacobs eloquently argued for the case of cities, although private initiatives and economic activity empirically generate urban development, it is social ideas, alongside the regulatory environment that shape private investments (Jacobs, 1961).

Hence, cities may be perceived as complex social systems. Social systems because their functional existence ultimately relies on social organisation, the latter seen as a high level of complex organisation that manifests itself through 'a set of roles [that individuals and organisations play in society] tied together with channels of communication' (Boulding, 1956, p. 205). Complex systems because they are 'made up of a large number of parts that interact in a nonsimple way', and for which 'the whole is more than the sum of the parts, not in an ultimate metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole' (Simon 1962, p.468).

The emergence of complexity perspectives in economics, particularly advanced when discussing complex economic dynamics and heterogeneous interacting agent-based complexity (e.g. Arthur *et al.*, 1997; Arthur, 1999; Rosser, 1999, 2009), has constituted a notable effort in providing more realistic explanations of complex social systems, with potential for more effectively forging sustainable solutions. The growing body of economics research concerned with complexity ideas has been drawing inspiration from developments in the complexity movement in the mathematical, computer and natural sciences, which, in turn, has co-evolved with another interrelated scientific movement, that of systems thinking. The latter challenges our existing mental models and aims to 'replace a reductionist, narrow, short-run, static view of the world with a holistic, broad, long-term, dynamic view, reinventing our policies and institutions accordingly' (Sterman, 2006. p. 509). Both complexity and systems thinking have interrogated the narrow mechanistic investigation of social systems, such as communities, markets or economies, whereby, these are assumed to operate in relative isolation from external influences, to be well-defined, feature internally complete connections and to be amenable to disaggregation into their individual elements, such that system-wide synergistic or antagonistic effects are ignored (Georgescu-Roegen, 1971; Checkland, 1981; Loasby, 2012). Nonetheless, despite overlaps, similarities and compatibilities, complexity researchers have not often explicitly linked their work to the insights offered in the systems-based theory literature (Richardson, 2004; Andersson *et al.*, 2014). When viewed from an economics lens, the literature, in this respect, is in even shorter supply.

It is within this setup, that this paper has been shaped. The intention is to offer conceptual insights and spur discussions in relation to bridging more closely insights from contemporary economics research drawing on complexity science with those circulated in systems thinking. The following section provides a succinct overview of the complexity science movement and its translation into economics research. Section 3 brings into discussion the systems thinking body of knowledge and considers salient commonalities and differences, when compared to complexity perspectives. Section 4 dwells on the potential of contemporary systems thinking to further inform and enrich complexity economics. It does so by emphasising two key aspects: on one hand, the macroscopic approach to mathematically capturing the dynamics of systems, and,

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on the other hand, the role of interpretivism and inter-subjective meaning in shaping knowledge and solutions. To render the discussion more tangible, references are made to aspects touching upon urban sustainability, particularly energy demand side aspects of decarbonisation, such as energy efficiency in buildings and residential energy consumption choices. Section 5 concludes.

2. A conceptual overview of complexity perspectives in economics research

Complexity science evades a shared or commonly agreed definition, and is perceived more as a movement in sciences, rather than a theory or science *per se* (Arthur, 2015). Its origins can be found in the 1940s work of the mathematician and science administrator Warren Weaver, who presented the scientific challenge of dealing with problems of 'organized complexity'[1] (Weaver, 1948). He argued that 'we need something more than the mathematics of averages' (Weaver, 1958, p.15), and advocated for the power of computers and cross-disciplinary collaboration, when analysing complex systems. Modern sciences studying complexity constitute a collection of distinct research strands with some overlapping concepts, such as self-organisation, emergence and adaptive behaviour (Mitchell, 2009).

As in the case of complexity science, complexity economics[2] is also perceived as an umbrella term or research agenda, rather than a coherent body of thought (Foxon *et al.*, 2013). The use of complexity ideas in economics goes beyond what may fall under the 'complexity economics' label *per se*, and may be grouped under the banner of a 'complexity era in economics' (Holt *et al.*, 2011). This has largely emerged from frustrations with the unsatisfying explanations of economic phenomena offered by the prevailing standard economics[3] paradigm (Arthur, 1999; Beinhocker, 2007; Kirman, 2010). It has gradually evolved out of the work done by various strains of economics research that accept the inherently complex nature of the economy, signaling a new openness of the economics profession to ideas from other disciplines (Holt *et al.*, 2011). Behavioural and experimental research in economics, evolutionary, institutional, ecological and neo-Austrian economics, are closely intertwined with what is explicitly labelled 'complexity economics', whereas other schools of economic thought (e.g. Post Keynesianism) have only lukewarmly embraced it (Foster, 2005; Holt *et al.*, 2011; Foxon, *et al.*, 2013).

Despite the rather incipient and fragmentary nature of complexity thinking in economics, a common lining, running through these is that of complex dynamics, which relates to the multiplicity (and uncertainty) of system behaviour because of complex

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[1] Problems of 'organised complexity' are problems that 'involve dealing simultaneously with a sizeable number of factors which are interrelated into an organic whole' (Weaver, 1948, p. 539).

[2] The term 'complexity economics' was coined by the economist Brian Arthur and the theoretical statistician David Lane who increasingly diverged from the economics mainstream, and were critical in advancing the seminal complexity work at the Santa Fe Institute (Fontana, 2010).

[3] By 'standard economics', we to refer to large swathes of modern mainstream economics that continue to frame their economic analysis based on the methodological foundations of (unique and stable) equilibrium under constrained optimisation, which rest on an individualistic or atomistic approach to understanding aggregate economic phenomena. Along these lines, standard economics either equates the behavioural properties of an aggregated economic system to those of its individual components, through the deployment of the representative agent assumption, or simply purports that the summative behaviour of the system under analysis is a mere aggregate of the individual behaviour of its components (economic agents) (Keen, 2011).

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interactions. Complex dynamics have been associated in the literature (Rosser 1999, 2009; Holt *et al.*, 2011) either (1) with an overall, general level, understanding of complexity (labelled 'big tent' complexity in Rosser 1999) containing perspectives from cybernetics, catastrophe theory, chaos theory, and interacting heterogeneous agent-based complexity, or (2) with the more specific latter view of agent-based complexity to which many economists refer, when invoking complexity economics (labelled 'small tent' or 'narrow tent' complexity, Rosser, 1999, 2009). Agent-based complexity, often associated with the work of the Santa Fe Institute (Arthur *et al.*, 1997; Arthur, 2006) constitutes a more operational, formal modelling approach (under the guise of agent-based models or agent-based computational economics models) that tends to help hold together the otherwise quite diverse sets of ideas on what constitutes complex dynamics (Colander *et al.*, 2004).

Even when placed within more specific agent-based complexity settings, views on what constitutes complex dynamics across economics research are not necessarily straightforward. Nonetheless, one may relate, in this respect, to five core shared sets of inter-related notions and principles depicting complex dynamics in economics: (1) Evolving, adaptive, systemic interactions populated by nonlinearity, feedback and novelty; (2) Self-organisation and emergence; (3) Out-of-equilibrium embedded in suboptimal, heterogeneous behaviour; (4) Fundamental uncertainty and lack of full predictability and control; and (5) Historical time, non-reversibility and path dependence. Although common features depicting complexity views in economics have been extracted, and described at various stages in the literature (e.g. Arthur *et al.*, 1997, Rosser, 1999; Beinhocker 2007; Antonelli, 2009), we also provide here our synthesis of this literature, in order to both add to the debate, and particularly facilitate our subsequent discussions linking to systems thinking.

In relation to the first set of shared features, complex economic phenomena may be viewed through the lens of recursive loops and nonlinear interplay between interacting individual elements and the aggregate patterns they may form (Arthur, 2015). These interactions are systemic and internally generated, in that the behaviour of individual components, and that of the system, as a whole are strictly dependent on the micro and macro dynamic interactions that take place within the system (Antonelli, 2009). Evolving complexity also tends to be hierarchic, interpreted in the wider sense of intra- and inter-component dynamic linkages or interactions within and between subsystems of a complex system (e.g. a business firm, an economy), with or without a relation of subordination among these (Simon, 1962). Complexity-sympathetic economists associate these nonlinear dynamic processes with the evolutionary traits of knowledge creation, selection and diffusion, whereby agents relentlessly update, adapt, discard or replace their behavioural strategies and decision-making processes, as they explore, learn and interact with each other, within and across varying contexts (Lindgren, 1997; Loasby, 2012). These evolving complex dynamics defining economic system architecture may lead to 'genuine novelty' (Harper and Endres, 2012) or knowledge generation, as new combinations of ideas, capabilities and activities are imagined (Loasby, 2012), and as the economic systems' order and complexity grow over time (Beinhocker, 2007). The ability to endogenously produce novelty or surprise is the hallmark of the Complex Adaptive Systems (CAS) framework, which has been applied to important economic phenomena, largely side-lined or treated as anomalies in standard economics, such as innovation, market incompleteness and co-evolution, persistent heterogeneity, increasing returns or extreme events (Markose, 2005). When

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adopting a CAS angle, real-life economic systems are perceived as ‘not something given and existing but forming from a constantly developing set of technological innovations, institutions, and arrangements’ (Arthur, 2015, p. 1). Moreover, the capacity of interdependent heterogeneous agents to intentionally or purposefully generate new knowledge and produce novelty, highlights the role of endogenous technological change in explaining the complex evolving dynamic character of economies (Antonelli, 2009). However, in dynamic settings, where knowledge is continually changing, novelty can also translate, at the micro-level, into limited firm innovation or inferior ‘modularisation’ of its products and processes (Langlois, 2002).

A second shared set of principles portraying (agent-based) complex dynamics in economics is that of (bottom-up) self-organisation and emergence. The former refers to the interplay between many individual agents and their linkages, which endogenously results in changes in the system from the inside, rather than from certain exogenous controlling factors (Gilbert *et al.*, 2015). ‘Emergence’ is a paramount theme unifying various strands of complexity-based economics research. Emergent properties are typically taken to refer to ‘macroscopic regularities based on micro-scale variability’, i.e. occurring when the nature and existence of a property of a system at a higher level, depends on system components interacting in lower levels, but cannot be linearly derived from these (Robert *et al.*, 2017). The notions of self-organisation and emergence replace the standard micro-foundations of macroeconomics, with the idea that higher-level economic patterns (e.g. under more stable or unstable forms of macro-relations and dynamics) are endogenously produced by the interplay between a diverse collection of a multitude of agents and rule-systems (Markose, 2005; Kirman, 2016). The concept of emergence is, nonetheless, elusive and nebulous, with little distinction between emergence as a process, and emergence as a product, although notable efforts have been made to extract fundamental features that need to be observed in the real-world, in order to qualify economic patterns as being ‘minimally emergent’ (Harper and Endres, 2012). In essence, self-organisation and emergence depict a process of nonlinear structural change, as well as creativity through acquired energy and knowledge, and the exploitation of ‘potential connectivity’, i.e. a non-equilibrium dynamic path (Foster 2005, 2006).

This leads us to the third set of complex dynamics features which covers the principle of complex systems operating out-of-equilibrium that are embedded in suboptimal time-varying and heterogeneous behaviour of diverse agents. Operating far from a general equilibrium or steady-state is typically argued by complexity economists to be the usual or natural state of an economy, which is always open to reaction and follows a process of continual change (Beinhocker, 2007; Antonelli, 2009; Arthur, 2015). Worthwhile noting though, that out-of-equilibrium does not necessarily translate into no equilibrium at all, since dispersed local interactions between agents can lead to higher-level emergent order that sometimes resembles equilibrium outcomes (pseudo-equilibrium), although not along the standard economics lines of a unique global optimal equilibrium (Arthur *et al.*, 1997; Rosser, 1999). Nonetheless, out-of-equilibrium dynamics are essential for technological and organisational innovation to occur, since the latter is both the result and cause of the former (Antonelli, 2009). Most market-based economic phenomena and the observed patterns they generate are ultimately possible because of the significantly different behaviour of the different individual firms and households (Hayek, 1967). Diversity in individual behaviour is vital to the functioning of economies or cities, since evolutionary dynamics is endogenously generated

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by behaviours in interaction, within increased cooperative and complementary, rather than competitive settings (Allen, 1994). Complexity economists acknowledge that people make socioeconomic choices differently, through a combination of inductive thinking, rational behaviour, social comparison, imitation, repetitive behaviour and the cognitive limitations of the actor (Arthur, 1999). Standard economic behaviour assumptions, which, primarily depict all individual economic agents as self-interested, atomistic, continuously optimising, fully rational, and bundled together under the 'representative agent' banner have been discarded in complexity perspectives. Instead, attention is drawn to empirically backed features of economic behaviour, along the lines of purposeful (non-maximising, intentional) individuals with heterogeneous preferences, and local and limited knowledge, and who may not necessarily collectively achieve an efficient aggregate state (Antonelli, 2011; Kirman, 2016). There is a mix of *homo economicus* and *homo psychologicus* traits compatible with other heterodox economics thinking, such as ecological economics (Jager *et al.*, 2000), not to mention the concept of 'bounded rationality' originating from the work of Herbert Simon, which cross-fertilised many fields, and stands at the core of behavioural economics research (Simon, 1955; Kahneman, 2003). In a nutshell, there has been 'a movement from an economics of rationality, selfishness, and equilibrium, to an economics of purposeful behavior, enlightened self-interest, and sustainability' (Holt *et al.*, 2011, p. 364).

The standard criteria of (specific or accurate) prediction and control for a valid scientific theory (traditionally deployed in the physical sciences) has long been argued to be less reliable or appropriate for the evaluation of theories targeting more complex (highly organised) animate processes (e.g. the theory of evolution) or social phenomena (e.g. the theory of social structures) (Hayek, 1967).[4] Nonetheless, the main validation appraisal criteria used in standard economics continues to be based on normative predictive success that entertains certainty or quantifiable risk. This is despite that entrepreneurship, economic evolution, and increased organised complexity, manifested through rising wealth in real-world economic settings take place under radical or fundamental uncertainty, which entails the absence of knowledge about the full set of events faced and the likely probabilities of their occurrence (Foster and Metcalfe, 2012). Fundamental uncertainty, unpredictability and lack of complete control of responsive processes (by individual actors) are instead defining features of complex adaptive systems (Aagaard, 2012; Turner and Baker, 2019). The future of economic dynamic processes is unknowable and less amenable to probabilistic anticipation, partly due to unexpected or indeterminate consequences of human action (Dequech, 2000). This suggests that economic actors, such as entrepreneurs can never fully optimise their production plans with certainty, since it is impossible for them to foresee the portfolio of actions adopted by other entrepreneurs, with whom they entertain an economic relationship (Harper and Endres, 2012). Alongside such structural inconsistencies and coupled with waves of ongoing technological change, the presence of real-world fundamental (deep) uncertainty further works to undermine

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[4] However, this is not to say that a more general kind of 'pattern prediction', as opposed to the specific predictions of individual events (favoured by the scientific method) is not testable and valuable for the study of complex phenomena (Hayek, 1967). Further, in the case of cities, although their future is largely unpredictable because of their complex nature, 'routine prediction' (linked to how cities function more routinely) might be nonetheless possible, despite the conditions under which this might take place being unknown (Batty, 2018).

system control, placing the economy into a continuous disruptive state and, thus, further eroding the deductive rational behaviour approach of standard economics (Arthur, 2015). Accepting the lack of certainty, of control and of specific predictability, including the ambiguity of the claims of universal determinism that these would imply (Hayek, 1967) has crucial economic policy implications. This is because policy effectiveness may benefit from learning how to influence (rather than aiming to control) complex economic systems, and guide evolutionary pressures towards desired societal outcomes (Colander and Kupers, 2014).

Finally, complexity perspectives in economics have a common interest in the traits of historical time, non-reversibility, and path dependence. These are strongly related to the endogeneity of knowledge processes and technological change (generated by a myriad of inter-related diverse agents), and the overall economics of innovation, which may be regarded as a distinct area of inquiry that shapes complexity insights (Antonelli 2009). The historical approach to time allows for the existence of evolutionary qualitative change in economic processes, as opposed to the concept of logical time deployed in the mechanistic epistemology of standard economics, which knows only 'locomotion [that] is both reversible and qualityless' (Georgescu-Roegen, 1971, p.1). Historical time facilitates the understanding of the interdependencies and circular causation between structural change and innovation, which are ultimately two inseparable parts of a single process of economic development (Antonelli, 2009). It points to the non-reversibility of economic dynamics, in that these can neither follow the same course of events or states in the reverse order (irreversible change), nor entertain a given state more than once (irrevocable change, such as the entropic degradation of natural resources via economic production processes) (Georgescu-Roegen, 1971, 1986). Since humans exist 'not only in time and space but in history' (Boulding, 1956, p. 205), historical time acknowledges the importance of social-institutional contexts in impacting and being impacted by human behaviour. Thus, the historical feature of economic dynamics is closely interweaved with the notion of path dependence. The latter, central to describing stochastic dynamic processes, generally relates to the locks-in effects of certain socioeconomic, technological, institutional and behavioural practices, and their endurance over time (Levin *et al.*, 2012). Path dependence is a major channel for translating complexity insights into economics. The concept is is 'most apt to understand the process and the outcomes of the interactions among myopic agents embedded in their own context and constrained [but not determined] by their past decision, yet endowed with creativity and able to generate new knowledge by means of both learning and intentional innovative strategies, as well as through structural changes' (Antonelli, 2009, p. 636).

3. Systems thinking and its commonalities and differences in relation to complexity approaches

Similar to the complexity movement in sciences, systems thinking eludes a commonly agreed definition. However, the literature points to two main attributes that shape this body of research: a cognitive and a communication dimension. The first describes systems thinking as an iterative learning process, a mental framework or worldview. This encompasses core values and assumptions concerning reality, and harnesses cross-disciplinary cognitive skills targeted at embracing interrelationships and dynamics, rather than things, objects or static snapshots (Senge, 1990; Behl and Ferreira, 2014).

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It is a way of thinking or research endeavour that asserts the role of relationships, patterns and context, whilst advocating for a paradigm shift away from parts to whole, from quantity to quality, from objects to interactions, from measuring to mapping (Capra and Luisi, 2014). Any emphasis on system wholeness occurs by bringing under the spotlight the dynamics of the system's internal structure, interactions and interdependencies. The second attribute insists on an often visual language that dwells on the notions of interdependencies, feedbacks and systems, on seeing the big picture when addressing particular societal challenges, and on asking 'what-if' questions about likely impacts of redesign interventions (Goodman, 2000; Arnold and Wade, 2015).

The origins of systems thinking are often associated with Ludwig von Bertalanffy's general systems theory (GST), which advocated for a general science of wholeness to better understand the workings of complex open systems (those that exchange matter and energy with their external environment) (Bertalanffy, 1950).[5] A common concern of Betallanffy's 'organismic biology' and other fields, with the principles of organisation, order and inter-connected wholeness of a system, led him to subsequently develop the GST idea (Bertalanffy, 1968; Reber, 2010). Notably, linking to economics, is the early work of Kenneth Boulding, whose efforts were geared towards translating GST into a 'skeleton of science', capable of providing a generalised theoretical framework of systems that would cut across and coherently connect widely different disciplines (Boulding, 1956). Another prominent example is the work of Friedrich Hayek, whose view of the economy, as a complex system of interacting individual and social rules of conduct was strongly influenced by Bertalanffy's insights (Rosser, 2010; Lewis, 2016; Festré, 2019). For instance, as noted in Lewis (2016), Hayek drew inspiration from GST to develop his account of the market economy as a complex adaptive system, i.e. displaying higher-level emergent properties (such as the coordinative power of the price mechanism) that arise from the interactions of individuals governed by certain systems of formal legal rules and informal social norms.

Overall, the complexity approach and systems-based perspectives have been highly complementary, have co-evolved and influenced each other. Some argue that the complexity science movement emerged as a continuation of what was done in cybernetics, general systems theory and chaos theory (Cilliers, 2001). Put differently, the complexity perspective may be currently perceived as a more recent extension or distinct offshoot of systems-based theory or thinking, rather than as an inseparable part of this (Ramage and Shipp, 2009; Verhoeff *et al.*, 2018). Others support the view that the complexity movement has changed the traditional systems thinking perspective, which was associated, particularly at its height in the 1960s, with a top-down control approach (Batty, 2018). It influenced system thinkers through the formalisation of central concepts, such as evolution, adaptation, emergence, and self-organisation (Merali and Allen, 2011).

As such, the literature points to considerable overlaps and strong connections between the complexity science movement, including its application in economics, and systems thinking. First, thinking in terms of complex evolutionary dynamics is also a hallmark for systems-based thinking. It stresses nonlinearity (an effect is disproportional to its cause), and feedbacks or causal multi-loop dynamics (Forrester, 1961;

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[5] Ludwig von Bertalanffy's general systems theory emerged in the 1930-40s, whereas the term 'systems thinking' appeared much later, in 1986–87 and is attributed to the systems scientist Barry Richmond (Arnold and Wade, 2015).

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Grösser, 2017), as well as the role of evolutionary processes and adaptive interactions, favouring the selection of some agents to the detriment of others, although not necessarily for the benefit of the overall system's long-term success (Sterman, 2006). Second, as with the complexity movement, interconnectedness, in terms of interactions between system elements (e.g. agents) is also the essence of systems thinking. The latter typically depicts these under the form of inter-connected wholeness or holism, which translates into the whole being greater than the sum of its parts, with analytical priority given to causal mechanisms and the relationships between system components, rather than to the components themselves (Senge 1990; Cilliers, 2001; Behl and Ferreira, 2014). Systems thinking does not treat economic phenomena as simple aggregates, but rather places the onus on the systems' internal structure and dynamics, on its internally generated interactions and interdependencies that may exist within and between its parts or subsystems. Both systems and complexity perspectives subscribe to the worldview that 'more is different', which works to undermine the vision of society as a mere aggregate of individuals (Anderson, 1972). Third, under both views, interactions between system elements within a system, and between a system and its environment occur within a landscape of diversity in the system's dynamic behaviour and in its internal inter-component interactions. As in the case of complexity perspectives, systems thinking stresses that such dynamics typically lead to the sub-optimal or underperforming behaviour of the system as a whole (Sterman, 2006). It portrays living (social) systems as open, nonlinear and able to maintain 'ordered steady states' under non-equilibrium conditions, i.e. operate stably, whilst being far from equilibrium (Loutfi and Moscardini, 2003; Merali and Allen, 2011). Fourth, although a systems-based perspective largely entertains the assumption of structural perseverance (feedback structure remains the same), once the boundaries of the system are defined (Merali and Allen, 2011), it does acknowledge limited predictability and irreducible uncertainties, as core features of social system change dealing with human values and motivations. For instance, new structural mechanisms or factors that may appear in a social system may be accommodated through mental flexibility and the willingness to redraw system boundaries and redesign the system (Meadows, 2002). Indeterminism is commonplace in the evolution of economic systems, whose essential parameters change profoundly and unexpectedly with the passing of history (Boulding, 1987). Aggregate economic processes are characterised by irreducible uncertainty, and, as such, they are inherently unpredictable in their totality, implying that 'prediction is no test of human knowledge' (Boulding, 1987, p. 116). Fifth, the importance of historical time and path dependence in helping explain observed resistance to policy intervention or change in the *status quo* is also widely acknowledged in systems thinking (Sterman, 2006). The dynamics of flows accumulating into stocks may lead to long time delays, further complicating efforts to break away from undesired path dependence.

Considering the above mutual features, one may infer that complexity perspectives and systems thinking rest on the shared ontological foundation of 'open systems'. Following elaborations on the meaning of open systems in economics in Chick and Dow (2005), we refer to real-world social systems as being open in that they entail boundaries, limits and connections with their surrounding environment, but of a fuzzy, provisional and changeable sort. Further, they display structures that are not predetermined, but mutable, ever-rolling and evolving, via inter-relationships between system elements, e.g. agents, who, in the presence of fundamental uncertainty, react, adapt, innovate and create. An open systems approach focuses on the consistency of

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the relation between theory and reality, although ontological openness does not necessarily prevent the use of theoretical closure, when analysing real economic systems, as long as awareness about the provisional or temporary nature of such closure remains in the foreground (Chick and Dow, 2005).

Despite this shared ontological basis, when adapting insights from complexity and systems thinking to economic analysis, the complexity movement is argued, though, to have proved more attractive, partly due to the economists' preference for the type of formal models that have been advanced, with the rise of computing power and simulation techniques, under the complexity perspective (Gilbert *et al.*, 2015; Turner and Baker, 2019). However, we contend that more explicitly bridging complexity economics with systems thinking could potentially shape a stronger investigative framework, more conducive to both intra-disciplinary pluralism, within the economics field, and heightened dialogue between economics and other disciplines.

4. Connecting complexity economics to systems thinking, with illustrative discussions applied to urban decarbonisation and residential energy demand

Complexity thinkers focusing on urban dynamics often consider cities as aggregates of multiple bottom-up decision-making agents, interactions, aspirations and processes, in relation to how people organise their social-economic activities in space and time (e.g. Batty, 2018). They specifically orientate their analysis on processes of change (Nel *et al.*, 2018). However, this may overlook the factors that work to affect the 'self' in self-organisation, such as the overall existent system structure, asymmetric power relations and the presence of fluid boundaries operating at different scales or system-levels (Gilbert *et al.*, 2015). When conceptualising and analytically investigating dynamic behaviour including self-organisation, the literature tends to be split in two approaches. It either underscores the multitude of dynamic patterns or properties at the system or macro-state level, arising from the interactions of micro-diverse agents (i.e. microscopic approach), or associates the overall system dynamic behaviour with a relatively stable system structure (i.e. macroscopic approach) (Gilbert *et al.*, 2015). These perspectives also build on different mathematical approaches, which nevertheless have significant potential for interlinkage.

Further, cities fit into the definition of complex adaptive systems, in that they are not fully integrated systems, but rather characterised by highly decomposable structures, ordered evolutionary processes and selective connections between actors, who continuously innovate through a mix of specialisation between, and variation within, activity domains (Loasby, 2012). These connection-shaping dynamics are not only technological, organisational and operational, but also cultural, social or ideological, in terms of commonly upheld beliefs in the presence of novelty, uncertainty and subjective knowledge (Foster, 2017). The interpretive element (or the social construction of meaning) pertaining to complex dynamic systems is a crucial feature defining systems thinking, and is closely in line with the cognitive and communication dimensions of this body of research (Senge, 1990).

The following sub-sections further explore the two systems thinking principles alluded to in the above. First, we investigate the macroscopic perspective to depicting complex system behaviour. Here, we argue from a mathematical perspective because

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it illustrates both the approaches' differences and potential for integration. Second, we explore the contribution of the interpretive dimension of systems thinking to knowledge generation. We argue that these two systems thinking principles have the potential to add value to complexity economics research, and enhance its coverage and depth in understanding and solving sustainability challenges. So that we provide some illumination, as to the added value of bringing these two dimensions into a hybrid complexity economics—systems thinking approach, we dwell on more specific urban sustainability issues, namely decarbonisation, and more pointedly, energy demand side aspects, such as energy efficiency in buildings and residential energy consumption choices.

4.1 Macroscopic and microscopic mathematical perspectives to modelling complex social-economic systems

Mathematics is indispensable for the systematic analysis of complex phenomena and the general description of the abstract patterns they may generate that are not accessible via our senses (Hayek, 1967). Mathematical perspectives to modelling complex social-economic systems may be grouped according to the level of granularity deployed, when analysing the dynamics of interactions between inter-dependent elements: a macroscopic and a microscopic approach. The former is primarily concerned with mathematically investigating the dynamics of the system as a whole and of higher-level or generalised inter-component interactions that endogenously drive the system's behaviour and internal structure, whereas the latter tackles complex dynamics at the lower-level, in terms of interactions between individuals (subjects or objects) that lead to the emergence of higher-level patterns or system-wide behaviour.

Moreover, economics perspectives of complexity may analytically refer to either computational complexity or dynamic complexity (Rosser, 1999, 2009). Computational complexity is associated with the macroscopic complex system perspective, in that it explores higher-level inter-component dynamics of the system, while assuming the system under analysis is well behaved, i.e. exhibiting smooth and continuous behaviour. It uses computable measures to quantify system complexity, such as Kolmogorov complexity and stochastic complexity (Rissanen, 1987), which are embedded in algorithmic concepts, and anchored on fundamental mathematical concepts in information and probability theory.[6]

Dynamic complexity can relate to system-level, macroscopic behaviour, as well as to microscopic approaches to complex systems. At the macroscopic level, it may be associated with nonlinear continuous systems, such as feedback loops used in cybernetics and system dynamics modelling (Wiener, 1961; Forrester, 1961) or may exhibit discontinuities, such as bifurcations or chaotic dynamics (Medio and Gallo, 1992; Lorenz, 1993). When placed within a social context, chaotic dynamics essentially recognise that the mechanistic representation of market economies can only be temporary, since their dynamics are entrenched in evolution and structural change,

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[6] Kolmogorov complexity measures the minimum length of a 'computer program' (reflecting computational resources) which is required to describe an (economic) entity or an object. Likewise, stochastic complexity measures the shortest 'computer program' required to describe a (economics) dataset. For instance, Kolmogorov complexity was used to compute the complexity of financial systems (Maslov, 2008), whereas stochastic complexity was deployed to investigate the efficiency market hypothesis of stock markets (Shmilovici *et al.*, 2003), or that of national electricity markets (Papaioannou *et al.*, 2019).

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and their precise trajectories are chaotic (sensitivity to initial conditions and unpredictability) (Allen, 1994). Dynamic complexity can also be linked with microscopic complex systems presenting smooth emergent behaviour at the macro-level, which can only be induced from below by micro-level transitions and interactions at the elemental (inter-connected agent) level of the system (Harper and Endres, 2012). The microscopic perspective is typically associated with (as adopted in our paper) agent-based or 'narrow tent' complexity (Rosser, 1999), which distinguishes itself from the earlier complexity (macroscopic) work of cybernetics, catastrophe theory and chaos. Although both macro- and microscopic mathematical formulations are deployed to analytically frame system complexity aspects, it is the latter, and not the former that is the workhorse of contemporary complexity economics.[7]

The microscopic analytical complexity perspective in economics (and elsewhere) draws on the 'mathematics of emergence' (Bar-Yam, 2004; Cooper, 2006; Cucker and Smale, 2007). These include Markov chains (Banisch, 2016), cellular automata (Evans, 2015) and process algebra (Baeten, 2005),[8] with examples of emergent behaviour in economics being discussed with reference to emergent capital formation (Harper and Endres, 2012) or emergent property rights (Langlois, 2002), or more specifically, within the context of decarbonisation, to domestic electricity demand and occupant behaviour in buildings (Widén and Wäckelgård, 2010; Virote and Neves-Silva, 2012; Patidar *et al*, 2016). Unlike macroscopic mathematical perspectives, the microscopic approach to dynamic complexity does not contain any counterpart generic measures to quantify the complexity or characteristics of emergent behaviour. The equations underpinning the microscopic system behaviour can be instead aggregated in some mathematical sense to generate equations describing macroscopic system behaviour (Le Boudec *et al.*, 2007; Banisch, 2016), but not vice-versa. In other words, the characterisation of emergent behaviour can be inferred analytically, in some complex systems by scrutinising the mechanisms underpinning the transitions and interactions at the micro-level, using approximation methods, such as mean field theory and process algebra (Damper, 2000; Latella *et al.*, 2015).

Mathematical methods deployed for the quantitative methodological formalisation of systems thinking (e.g. system dynamics modelling used for policy design) fall under the macroscopic perspective, since they are less concerned with the micro-to-macro emergence phenomena, and emphasise instead overall system dynamic behaviour, and interactions between its components at the higher- or more aggregated levels. As systems thinking was significantly influenced by the nonlinear dynamics of feedback mechanisms deployed in cybernetics and control engineering (Merali and Allen, 2011), its formal simulation modelling methodological apparatus also largely adopt a macroscopic approach to complex dynamics. This is less alluded to (we think,

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[7] We are not addressing in this paper the operational or computing aspects of the modelling methods, which include agent-based modelling (ABM) and system dynamics modelling (SDM) as methodological frontrunners of (microscopic) complexity economics and, respectively, (macroscopic) systems thinking. We focus instead on addressing the theoretical and fundamental aspects of the methods. Instances of integrating ABMs and SDMs are relatively sparse as this is an emerging literature, and even sparser in the economics of sustainability transformations, such as city decarbonisation (e.g. Jo *et al.*, 2015; Shafiei *et al.*, 2012).

[8] Markov chains are stochastic processes in which individuals/objects undergo transitions between discrete states subject to probabilistic rules. Cellular automata also involve transitions but of cells residing in a regular grid. The transitions are also governed by rules, which can be either deterministic or probabilistic. Process algebra comprises a set of mathematical axioms which define concurrent communication between objects in complex systems. Fuzzy set theory deals with situations when the variables cannot be defined precisely either deterministically or probabilistically but are defined instead as members of sets.

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unfortunately) in what is typically considered to be complexity economics. The system dynamics method, founded by the leading systems scientist Jay Forrester originates in engineering, control theory and servomechanisms design, and is chiefly preoccupied with nonlinear relations (multiple interacting feedback loops), circular causality, stock and flows, delays and other endogenous or internally generated mechanisms capable of capturing a rich spectrum of possible system behaviour (Sterman, 2001; Richardson, 2011). All these features determine the system's dynamics, which can reflect system stability or system breakdown and act to help explain policy resistance, 'the tendency for interventions to be defeated by the response of the system to the intervention itself' (Sterman, 2001, p. 8). They also enable decision-makers to examine likely unintended consequences from intervening actions, which may provide useful insights, as long as no significant new mechanisms or factors (not incorporated in the modelled structural dynamics of the system) appear during the time span modelled, for which their inclusion would entail the reformulation of the mathematical model of causal relations (Allen, 1994; Merali and Allen, 2011). Although the systems thinking literature may encompass quantitative simulation models drawing on fuzzy mathematics or fuzzy set theory allowing the incorporation of imprecise or ambiguous factors driving system behaviour (Khayut *et al.*, 2014), e.g. the fuzzy system dynamics modelling of renewable energy policies (Mutingi and Mbohwa, 2013), its macroscopic approach is typically rooted in the mathematics of well-defined nonlinear differential and integral equations (Drazin, 1992; Adams *et al.*, 2014), which can be associated with both deterministic and stochastic models (Sterman, 2018). System dynamicists typically approach the dynamics of complex social systems from a continuous conceptual view that transforms discrete decisions into continuous patterns of behaviour, which allows them to centre their analysis, for instance, on the policy structure determining decisions (Richardson, 1991). Classical examples include Forrester's early system dynamics modelling of urban and industrial dynamics (Forrester, 1961, 1969), or more recent work, carrying on this legacy, and adapting it to the policy challenges of urban sustainability and energy decarbonisation, such as the system dynamics modelling of urban sustainability performance (e.g. Tan *et al.*, 2018) or of the energy consumption in the residential building stock (e.g. Onat *et al.*, 2014).

A poignant illustration of the differences and similarities between the microscopic and macroscopic perspectives is that pertaining to modelling the social-economic and environmental impacts of housing energy efficiency (HEE) interventions. In this context the 'system' may be defined as the residential housing sector, which reacts to HEE interventions, but equally as the network of interactions that affect home owners' decisions to take up HEE interventions. This system is complex for many reasons. The causal pathways linking its variables are multidimensional with feedback pathways. System boundaries are not universal, but can only be defined from the perspective of the issue to be explored (Beer, 1979). Moreover, the affected population transcends those receiving the interventions to their neighbours and social networks. Incorporating delays is important, as variables can have very different response times to stimuli. On one end of the spectrum, installing double-glazing can have a swift effect on energy demand (unless taken back by rebound effects), whereas, at the other end of the spectrum, the glazing's effect on decreasing (albeit unintentionally) indoor ventilation can have detrimental effect on health, which takes hold at a much longer time-scale. The response of the system variables to stimuli can also be highly nonlinear,

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meaning that the responses to stimuli are not additive: *ceteris paribus*, doubling the number of double-glazing installed in dwellings does not reduce energy use by half. Furthermore, both the administration of the interventions and the system responses to the interventions are strongly time-varying, and so dynamics is a key characteristic of the system being studied.

The microscopic approach typically advanced in complexity economics presents two major advantages that matter for exploring differentiated social and economic impacts of HEE interventions: capturing the heterogeneity of householders and their behaviour and allowing for the emergence of higher-level behaviour from low-level interactions that may entail adaptive and structural change (Epstein, 2006; Banisch, 2016). This is because, there is supporting evidence of mixed results from HEE interventions depending on the socioeconomic status of the population groups (e.g. the case of New York City in USA in Hernández and Phillips, 2015). In addition, a microscopic approach developed to simulate the behaviour of affected residents, pre- and post- large-scale area regeneration programmes, and during the transition phase can allow for emergent distinct behaviour in population groups depending on the strengths of their social networks (Chalabi and Lorenc, 2013; Egan *et al.*, 2013).

It can be argued, on the other hand, that there is often insufficient empirical evidence to power the decision rules governing the heterogeneity of population behaviour (Badham *et al.*, 2018). Hence, at best, the emergent behaviour can only be inferred retrospectively from simulating a diversity of decision rules. Importantly, from a mathematical perspective, it is easier to influence a system at the macroscopic, than microscopic level, because of the decentralised nature of the latter. This makes the macroscopic formulation of a system more amenable to interactions with policy makers, supporting an integrated management and planning of residential energy efficiency actions (e.g. Dyner *et al.*, 1995; Onat *et al.*, 2014). It gives more weight to feedback loops, and permits a clearer analytical mapping of possible nonlinear inter-component interactions and time varying causal mechanisms that may be at play within the internal structure of a system. This has relevant potential to complement the bottom-up complexity perspective, since the latter may run the risk of obfuscating the nature of the intermediate processes that link the micro-level rules of agent interactions with the higher-level emerging patterns (e.g. as argued in Pollitt and Mercure, 2017).

The microscopic approach, versatile in dealing with evolutionary change, can explore a range of possible system structures that may emerge, in principle, from low-level interactions. On the other hand, the macroscopic approach can help identify higher-level system nonlinearities, and point towards a (collectively) preferred course of (policy) action, contingent on the given system structure (e.g. Toka *et al.*, 2014, who used system dynamics to model policy options for the diffusion of biomass heating in the residential energy sectors, within a given mathematical formulation of the new product adoption and growth dynamics). In other words, a mixed macro-micro mathematical modelling of complex social-economic systems (e.g. cities) would allow for the description of not only deterministic and probabilistic dynamics of nonlinear systems, but also of both structural perseverance and structural qualitative change, of 'average dynamics' and 'evolutionary drive' (e.g. innovation or exploration process in the form of unpredictable non-average perturbations within the system) (Allen, 1994, 1997). Moreover, from a policy viewpoint, a hybrid complexity-systems thinking stance that supports a mixed micro-macroscopic approach would require that cities connect with

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the national scale, so that consistencies between urban and economy-wide policies are ensured. With that said, mathematics is 'the language of theory but it does not give us the content' (Boulding, 1956, p.197). As such, we next move to the second attribute, often linked to systems thinking though underrated in complexity economics, the interpretive dimension.

4.2 The role of interpretivism and inter-subjective meaning

The built environment is a manifestation of our material culture, the latter defined as 'that sector of our physical environment that we modify through culturally determined behaviour' (Deetz, 1977, p.24). Hence, the fabric and form of buildings are essentially human-centric, produced to cater for the countless needs and desires of people. Within the context of decarbonisation, the importance of considering the wider societal aspects of energy demand and the social practices motivating energy use (Baker *et al.*, 2018; Shove and Walker, 2014) serves as a reminder of the inescapable human dimension of energy–economy–environment interactions, and helps reconsider the nature of meaningful climate action. Since the social sciences' purpose of investigation is to reflect on meaningful or purposeful human behaviour, and, thus, on an 'already-interpreted life-world', the interpretive dimension is ubiquitous in these disciplines, which ultimately are 'interpretations of interpretations' (Lavoie, 2011). Interpretivist research dwells on the meaning attributed to the patterns identified and seeks to contextualise observed or assumed higher-level generalities (Schweber and Leiringer, 2012). An interpretivist view accepts the limitations of knowledge, and adjusts its lens so that more focus is placed on subjective meanings, as well as the social construction of meaning (Berger and Luckmann, 1966; Schwartz-Shea and Yanow, 2011). It is less concerned about the individual's subjective meaning *per se*, relative to a specific culture or a specific conceptual scheme, and more about the inter-subjective meaning of individual agents, i.e. rendering intelligible the subjective meanings from one person to another (Lavoie, 2011).

There are two main channels via which an interpretive angle may be injected more strongly into economics research preoccupied with complexity perspectives. First, there is the purposeful action or intent of the 'object' under investigation, i.e. the human element with its panoply of beliefs, imagination, individual and collective values, social and cultural norms. Second, there is the epistemic stance that reflects on the nature of human knowledge to be expected or generated. This links to the subject carrying out the research, hence, to the scientist's view, experience and background, to the role of persuasion in the economy and human meaning in speech (McCloskey, 2016), of ordinary or human logic as opposed to formal classical logic (Dow, 2012), and, overall, of argumentation, communication, criticism and countercriticism. Both these interpretive angles are accommodated for in the systems thinking literature, which can incorporate 'softer' factors, in the form of human perception, worldviews and values, when exploring complex social systems (e.g. the 'soft systems methodology' advanced in Checkland, 1985 or 2000).[9]

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[9] Soft systems methodology 'is double systemic: it is itself a learning system, and within that system it uses systems models, models of human activity systems. It accepts that such models are not models of parts of the real world, only models of ways of perceiving the real world, that is to say, models relevant to debate about "reality"' (Checkland, 1985, p. 821).

In relation to the first channel, although positivism or objectivism has been easing its grip in economics, there remains, in general, a strong methodological bias against interpretive/qualitative aspects, which are still not seen as integrative parts of scientific work (Lavoie, 2011). Subjective elements, such as human emotions and vivid imaginations, which help drive entrepreneurial creativity and innovation in the presence of highly complex and uncertain circumstances, and which are widely disregarded in conventional economic theory, have been acknowledged in parts of the economics literature on complexity, although their clear incorporation remains a challenge (Foster and Metcalfe, 2012). Overall, it may be argued that the interpretive dimension of complex social phenomena has been explored to a lesser extent in complexity economics, but more openly embraced in systems thinking. Although most system thinking scholars have been operating outside of economics (e.g. management sciences, public policy, public health), some do stem from the economics profession or have engaged with the economics literature.[10] One may cite here earlier work blending subjectivism with complexity and systems thinking, such as that of the heavyweights Friedrich Hayek and Ludwig von Mises, leading figures of Austrian economics and influencers of other strands of economic thought, e.g. evolutionary and behavioural economics (Beck and Witt, 2019; Festré, 2019; Lavoie, 2011). Citing Lewis (2017, p. 13), 'Hayek's account is one that suggests that people are creative beings who can respond differently to the same set of external circumstances'. However, from our reading of the literature, the interpretive dimension is generally overlooked in modern complexity economics research. It may be partly because (agent-based) complexity thinking in economics has largely adopted a 'hard' complexity science approach[11] drawing on formal quantitative modelling under a positivist, or, at the best, a post-positivist perspective (Phelan, 1999; Morçöl, 2001; Yolles, 2019).[12] Moreover, the philosophy and science of interpretation (such as hermeneutics) has achieved, in its modern revival form, little headway in translating its social science methodological insights into the realm of economics (Lavoie, 2011).

Similar trends depict the economics literature evaluating strategies for decarbonising cities and economies, in that it fares poorly in adopting qualitative approaches and understanding the human dimension of energy-economy-climate interactions, such as political will, public acceptance, social norms, institutional constraints and non-market barriers (Scrieciu *et al.*, 2013; Pfenninger *et al.*, 2014). Complexity economics

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[10] There also are several minority strands of economic thinking, such as institutional economics and Post Keynesianism that depart from the objectivist bias and regularly incorporate interpretive elements in their economic analysis (Lavoie, 2011). However, since links between these and the systems thinking literature are not explicit, direct or necessarily strong, we do not further relate to this body of research, although we do acknowledge its complementary contributions.

[11] The hard complexity approach, also referred to as (neo-)reductionism is argued to be primarily concerned with the quest for finding overarching simple generative rules that underlie complex systems (e.g. through the use of bottom-up agent based computer simulation modelling) (Richardson, 2008). It has been applied largely in the natural sciences, computer science and economics, as opposed to the soft complexity approach that covers disciplines, such as management, cybernetics or humanistic studies (Yolles, 2019). The hard-soft complexity distinction is also based on personal conversations of one of the authors (ŞS) with Professor Michael Batty, 03.10. 2019.

[12] Key differences between positivism and post-positivism lie mostly in their epistemic stance. The former advocates for objective knowledge, fact-value distinction and universal laws, amongst others, whereas the latter acknowledges that there can only be limited generalisations, since a clear separation between subject and object is problematic and since knowledge is not objective, but of contextual or endophysical nature (Morçöl, 2001).

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is plagued by similar shortcomings, even though it is more able to capture the diversity in human behaviour, in relation to energy and the economy. Its methodological apparatus is inclined towards the use of formal quantitative simulation modelling frameworks, often in the form of agent-based models and network models (e.g. Bale *et al.*, 2013; Rai and Henry, 2016; Moglia *et al.*, 2017), to the detriment of interpretive research methods that could well complement their quantitative formal counterparts deployed in mainstream complexity perspectives (Andersson *et al.*, 2014). Although complexity economists, and theorists, in general, question the Newtonian notions of universal laws, strict determinism and objective knowledge, arguably they still adhere to a realist ontology (i.e. exploring an emergent self-organising world that exists objectively) and to offer generalisations about social phenomena, whilst admitting that complex interactions constrict our detailed or contextual understanding of reality (Morçöl, 2001).

Inter-subjectivism abounds in the creative process underlying economic decision-making and investment choices, i.e. participants in market economies interpret changes in their circumstances, and may act imaginatively, with potential for system transformation and innovation (e.g. see the work of the subjectivist economist George Shackle as discussed in Lewis, 2017). Exploring inter-subjective meanings is compelling for understanding the values, incentives and purposes pertinent to cognition and to interactions between the participants shaping a complex adaptive social system, values which are essentially different from the purposefulness or social-economic objectives of the system as a whole (McQuade and Butos, 2009). Moreover, such interpretive angles relate not only to actual changes in the current environment (facts), but also to potential changes that may occur in the future (expectations), depending on people's past lived experience (Hayek, 1952). From this perspective, interactions between the inter-subjectivism underlying the mental models of the actors involved in decarbonisation efforts and overall observed energy-economy trends and patterns do not readily fit within a positivist simulating framework but would require a completely different approach via an interpretative simulation framework and/or qualitative methods. Key interpretive themes, such as the relevance of social attitudes with respect to energy technology adoption, risk perception linked to energy retrofitting of buildings, subjective conceptualisations of household energy technologies, or the multidimensional aspects of trust and confidence when seeking to manage the expectations of those targeted by energy decarbonisation programmes would rather invoke modes of inquiry along non-quantifiable or non-generalisable lines. These may include narrative analysis, rich historical accounts, case studies and descriptive analysist of surveys and interviews, stakeholder engagement, scenario visioning and participatory approaches, critical and reflexive analysis, explorative storylines and stories, or modelling of interpretation, amongst others (e.g. for energy and climate economics related research, see Lutzenhiser, 2014; Karhunmaa, 2016; Longhurst and Chilvers, 2019 or Moezzi *et al.*, 2017). Interpretive reasoning may also be incorporated into more formal qualitative or mixed qualitative-quantitative modelling frameworks, although these continue to be in little supply in the literature on the energy demand side of decarbonisation. Examples include qualitative causal loop diagrams and qualitative and quantitative system dynamics models built in a participatory way, sociotechnical transition pathway storylines, or multi-criteria decision analysis incorporating both

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qualitative and quantitative criteria and assessments (Schweber and Leiringer, 2012; Cohen *et al.*, 2018; Eker *et al.*, 2018; Roberts and Geels, 2019).

The qualitative approach acknowledges the scientific validity of expert knowledge, and focuses on socially feasible instead of optimal solutions, as it tackles less rational or directly measurable social elements of end-user energy consumption choices (Shipworth, 2006), e.g. subjective perception of residential wellbeing in energy efficient housing manifested via the ability to open windows, and let in air, smell and sounds (Wågø *et al.*, 2016). Through the use of stories and narratives in particular, researchers targeting the energy-economy-climate nexus are enabled to pursue more creative avenues of enquiry, and generate a different type of evidence, oriented towards relationships between people and things, with socially engaging emotional, cultural or symbolic content that is largely absent in more formal data collection (Moezzi *et al.*, 2017). Such narrative methods help reinterpret key notions deployed in urban sustainability analysis, such as seeing barriers to energy efficiency improvements 'not as simple evidence of intervention failure but as constitutive features of social structure and social action' (Lutzenhiser, 2014, p. 149).

Furthermore, research is not only about answering questions, but ensuring the right questions are posed, that they are pertinent and legitimate, which, ultimately, can only be addressed qualitatively and not quantitatively (Lavoie, 2011). Put differently, methodological and theoretical choices, and the interpretation of their results are guided by a vision of how reality is put together, and understanding the latter is paramount to understanding the former (Colander, 1993). 'Intrinsic to the logical justification of all theory, formalist or non-formalist, is qualitative judgement' (Dow 1995, p. 729). Qualitative evaluations, alongside interdisciplinary dialogue, can also contribute to critically reviewing the fitness-for-purpose of decarbonisation modelling choices, and reflect upon relevant discrepancies between the properties of the modelled world and those observed in real-world settings (e.g. Wiese *et al.*, 2018). Interpretivism does not entail 'anything goes', eclecticism, 'rampant relativism' or the absence of criteria to knowledge buildup, but is rather achieved through criticism, dialogical contention, acknowledged diversity, evolving consensus and shared understanding (Lavoie, 2011; Dow, 2012).

This leads us to our second channel, through which the interpretive dimension may propagate in research: the epistemic stance of the scientist and her tolerance for methodological pluralism to knowledge generation. 'Systems of thought, no matter how objective they purport to be, have underlying emotional bases and values' (Jacobs, 1961, p.221). This remark made by the influential urbanist resonates with the systems thinking position on knowledge generation. Contemporary systems thinking provides an epistemological and methodological apparatus that departs from an exclusive positivistic thinking to a view that is also inclusive of interpretivist approaches, which permits it to explore more openly the role of human values, feelings and aspirations in moulding societies (Lane, 2001; Barton and Haslett, 2007). The investigative core of systems thinking is more rooted in open cognitive paradigmatic processes (Cabrera *et al.*, 2008), guides personal or societal philosophies and epistemologies (Magee and Kalyanaraman, 2009), and thus can accommodate for exploratory and interpretive approaches through reiterative learning (Goodman, 2000).

Mainstream complexity economics largely emphasises mathematical rigour, computing power and algorithms, and, overall, complexity perspectives, by their nature remain not that methodologically diverse, since they mostly pursue formal, quantitative

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modelling approaches (Andersson *et al.*, 2014). Even though post-positivism may engage a non-normative social understanding of knowledge generation that is closer, than its normative counterpart, to the epistemological stance of adaptive systems theory (McQuade and Butos, 2009), there is an unsatisfactory incorporation, in the complexity economics literature, of the idea that our scientific insights about economic systems is a social process of discovery, subject to interpretation and scrutiny from both within and outside science. Within this context, systems thinking may help widen understanding of the nature of the economy and broaden the methodological spectrum beyond simulation methods and mathematical formalism, often deployed in complexity economics. This calls for an epistemic stance rooted in methodological pluralism, described in the literature on economic methodology as a 'meta-methodological' position that argues for a range of methodologies to be critically discussed, shared within the research community, and their strengths and weaknesses understood (Dow, 2012). Nonetheless, methodological pluralism allowing for interpretivism to be combined or contrasted with positivism remains rare in complexity economics research. This is despite the integrative capacity of studies on complexity that would allow complexity science and systems thinking researchers to tap into various ontological and epistemological realms, and integrate real-word systems with metaphysical standpoints (Allen and Varga, 2006; Varga, 2014). One can draw inspiration, for instance, on the work of Peter Allen, who was a pioneer not only in the application of a mix of formal quantitative complex systems models, but also stressed the social construction of meaning, and the role of multiple evolving social values, emotions and intuition in shaping complex social systems (e.g. Connor and Allen, 1994; Allen and Varga, 2006; Allen, 2007).

We would emphasise, though, plurality in complexity-systems thinking methods, more through their separate, decoupled deployment, and less via their integration under a unifying analytical framework. In this respect, ideas circulated in parts of the non-mainstream economics literature for workable methodological pluralism, such as 'structured pluralism' that imposes a limitation on pluralism on the basis of some ground of understanding and interpretation (Dow, 2004) could help strengthen the epistemic connections amongst complexity perspectives in economics, as well as between the latter and systems thinking. For instance, at the local level, starting from a shared understanding of fuel poverty as a complex social problem, the vulnerability of households to fuel poverty and links to domestic energy efficiency interventions may be assessed, more in-depth, through observational ethnographics (e.g. Mould and Baker, 2017), which can be contrasted and compared to the complexity modelling of the social context of decision-making that quantitatively assesses the likely success of local authority interventions pushing for the uptake of domestic energy-reducing or low-carbon technologies (e.g. Bale *et al.*, 2013). From a wider, societal perspective, the formal simulation of agent-based dynamic complexity that examines the macro-outcomes, such as the adoption of low-carbon behaviours and technologies over space and time, from micro-level interactions (e.g. Rai and Henry, 2016) could be set against a qualitative mapping of diverse visions of energy transition, co-produced across different institutional settings or collective practices (e.g. Longhurst and Chilvers, 2019) or against studies of how the diversity of mental models and cognition shapes low-carbon behaviour.

Capturing the complexities of sustainably transforming our cities and economies would require, at least methodological pluralism and the co-existence of alternative economic perspectives (Cloete, 2017; Moffatt and Kohler, 2008). A hybrid complexity economics—systems thinking approach may help push in this direction, with a

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justification for methodological pluralism grounded in a mode of thought that consolidates the identified shared ontological open system position with an epistemic stance that is also formulated in open system terms. As Dow (2012, p. 139) summarises, 'within an open-system approach, there is no contradiction involved in arguing for one's own viewpoint, while respecting and being open to the viewpoints of others'.

5. Conclusions

The complexity science and systems thinking movements embed creative knowledge flows that have formed largely in response to the limitations of the traditional reductionist view to advancing science and our comprehension of the world around us. Their principles are ever more so important, when translated into social sciences and applied to the wicked challenges of shaping sustainable cities, and, overall, large-scale sophisticated social-economic systems. However, although the two strands of research are highly compatible, the literature applying these in the economics field, only occasionally have explicitly linked them.

Complexity economics with its emphasis on agent-based complex dynamics, and bottom-up emergence and self-organisation has spurred a strong strand of research with increasing potential to provide insightful explanations, representations, quantifications and modelling of real-life economic phenomena and their embeddedness in social systems. Having said this, we argue that complexity economics may gain from reforming itself, along two main lines of investigation connected to contemporary systems thinking. First, in addition to its emphasis on individual agent autonomy and interactions of increased granularity, complexity economics may benefit from valuing more the role of higher-level system structures and generalised, macro-level dynamics in influencing systemic change and long-term policy interventions. Second, its research agenda may be expanded and diversified by injecting a stronger interpretive dimension that more closely acknowledges the role of inter-subjectivity and the social construction of meaning, in shaping real-world complex economic order and social dynamics.

Systems thinking attributes that allow for macroscopic analytical formulations, on one hand, and interpretivist approaches, on the other hand could help (re)build bridges and solidify the methodological base pursued in complexity perspectives in economics. Methodological pluralism fostering dialogue between and across quantitative and qualitative methods, and stirring creative clashes amongst positivist and interpretivist methodologies, based on shared open systems epistemological and ontological foundations could be nurtured. Ultimately, when confronted with fundamental uncertainty, incomplete, provisional and consensual knowledge, unforeseen consequences, and changing social values, as in the case of urban sustainability challenges, a hybrid complexity-systems thinking approach would favour flexible, inclusive policies and societal actions. Thus, any interventions could be more readily revised and locally adapted, as we reconsider and progress in our understanding of the complexities populating inter-related sustainability challenges.

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