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Unpacking a Black Box: A Conceptual Anatomy Framework for Agent-Based Social Simulation Models

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Abstract: This paper aims to improve the transparency of agent-based social simulation (ABSS) models and make it easier for various actors engaging with these models to make sense of them. It studies what ABSS is and juxtaposes its basic conceptual elements with insights from the agency/structure debate in social theory to propose a framework that captures the 'conceptual anatomy' of ABSS models in a simple and intuitive way. The five elements of the framework are: agency, social structure, environment, actions and interactions, and temporality. The paper also examines what is meant by the transparency or opacity of ABSS in the rapidly growing literature on the epistemology of computer simulations. It deconstructs the methodological criticism that ABSS models are black boxes by identifying multiple categories of transparency/opacity. It argues that neither opacity nor transparency is intrinsic to ABSS. Instead, they are dependent on research habitus - practices that are developed in a research field that are shaped by structure of the field and available resources. It discusses the ways in which thinking about the conceptual anatomy of ABSS can improve its transparency.

Keywords: Transparency, Sensemaking, Model Structure, Model Description, Epistemology of Computer Simulation, Research Habitus

Introduction

1.1 Most readers of this journal are well aware of the strengths and limitations of agent-based social simulation (ABSS). ABSS allows researchers to construct complex hypothetical worlds out of relatively simple elements. It represents social reality with simulated objects, each of which can receive, process and respond to information at individual, local and aggregate levels. These objects can be created with a short code, covering only a small number of the properties of the things that they represent. Despite this initial level of reduction, ABSS models can produce complex social settings by generating varied instances of such simple representations and can develop simulated histories by allowing these instances to interact. Furthermore, as a given social context can be understood and represented in different ways, the complex hypothetical worlds created via ABSS offer subjective and partial depictions of social reality. Transitions in these two directions - from simple codes to complex entities and to subjective representations - entail both great potential and major complications.

1.2 Regarding its potential, ABSS accommodates integration of different ideas and supports development of alternative approaches to a research problem. In addition, ABSS is well known for its strengths in producing *relational knowledge* about the way in which people are connected. It enables researchers to observe the macro-level (e.g., collective, societal) implications of micro-level (e.g., individual, organization) interactions (see for example Axtell 2005; Arthur 2005; Tesfatsion 2006; Gaffeo et al. 2008; Delli Gatti et al. 2010; Page 2002). ABSS represents micro-level entities with computational objects and virtually grows the regularities of interest bottom-up, showing that plausible agents interacting in plausible ways could construct them (Epstein 1999;

Tesfatsion 2006). Hence, it can provide "*greater interpretive depth*" than other modelling approaches (Millington et al. 2012, p. 1027). This is a very important potential, because the micro/macro divide leaves a significant gap in our understanding of social phenomena (Wippler & Lindenberg 1987; Raub et al. 2011). In economics, for example, this gap accounts for the need to divide the discipline into two branches (see Janssen 1993 for alternative definitions of micro and macroeconomics).

1.3 Regarding its complications, both the complexity and subjective nature of simulated worlds imply the necessity of introducing and explaining large amounts of material and information. Hence, in practice many ABSS studies appear as black boxes and fall short of achieving their potential impact. A common approach in the agent-based modelling community for addressing this problem has been developing standards that help the effectiveness of communication. Contributions to such standards are predominantly based on social-ecological models. Grimm et al. (2006), Grimm et al. (2010), Grimm et al. (2017), for example, addressed this need by developing a standard format called the Overview, Design concepts and Details (ODD) protocol to "facilitate readability through stipulating a structure for the description with a logical ordering" (Polhill et al. 2008). While the format has been very successful and widely adopted for ecological models, its impact has been limited in social simulation (Polhill 2010). Pointing out limitations of ODD with respect to human decision making, Müller et al. (2013) expanded the Design concepts in ODD to make theoretical background and modelling decisions more explicit. Schlüter et al. (2017), furthermore, aimed to develop a generic framework that can capture decision-making in different theories to support communication and comparison of models. The authors focused on "what comes in (perception), what goes out (behaviour) and what happens in *between* (i.e., rules and representations that lead to the selection and execution of a behaviour)" (p 23, italic in original) to create their MoHuB framework (see also Graebner 2017).

1.4 In this paper, we aim to improve the transparency of ABSS following a different approach. Firstly, our aim is making it easier for various actors to make sense of ABSS. Sensemaking is the process of assigning meaning to and structuring the unknown (Waterman Jr. 1990). It entails organising information about an out of the ordinary subject in a framework (Starbuck & Milliken 1988) in order to restore some consistency between what is expected and observed, albeit in an altered configuration of expectations (Louis 1980). Ancona (2012) points out that during sensemaking, actors move "from simple to complex and back again". Complex in this sense is the territory of new information and actions. As the information is structured though, "the complex becomes simple once again, albeit with a higher level of understanding" (p.4). In this paper, instead of a technical standard or protocol, we aim to develop a simple and intuitive conceptual model of ABSS that can facilitate this higher level of understanding. Secondly, instead of finding our insights on social complexity in the natural sciences, we direct our inquiry towards the nature of social reality. We take this direction not because we think social and other systems do not intersect, or that models and metaphors that work for both cannot be found, but to take the opportunity to consider what is left out in such general and generic approaches.

1.5 In the sections that follow, we follow three intersecting paths. First, in Section 2, we build a link between social theory and ABSS by relating social complexity to the agency/structure debate in social theory. This analysis also allows us to relate the potential strengths of ABSS to one of the major meta-theoretical challenges in social science research. In addition, it provides us with insights for making sense of social reality, which we use for our framework in Section 4. Second, in Section 3, we address the transparency of ABSS. We build on recent discussions of the epistemology of computer simulation and deconstruct the common criticism that agent-based simulation is a 'black box'. This analysis yields a classification that is useful for improving the transparency of ABSS, covering criteria, levels, objects and mediums of transparency and potential sources of transparency problems. Third, in Section 4, we present an alternative way of thinking about the conceptual structure of ABSS. In biology, anatomy is the study of the structure of living things. Among its major uses are enabling an understanding of bodily functions, and identifying similarities and differences between individuals and species. In addition, in art, anatomy facilitates more realistic representations of living things. We use the metaphor of anatomy to describe the conceptual structure of models. Our aim in examining the essential parts of ABSS is to find an intuitive, coherent and succinct answer to the question: *what is the conceptual structure of ABSS*? We propose a framework with five elements to assist the process of sensemaking. Section 5, we build upon our analysis in Section 3, and discuss the ways in which the conceptual anatomy framework can improve transparency of ABSS. The framework clarifies what an ABSS is and does and so we expect that it will be useful for teaching ABSS, model-building, model description and reviewing literature.

Social Complexity of Agency and Structure

2.1 While the complexity of social reality is a ubiquitous theme in ABSS research (e.g., Arthur 2005; Tesfatsion 2006;

Gaffeo et al. 2008; Delli Gatti et al. 2010; Edmonds & Meyer 2013), this theme is not well grounded in social theory. It is not adequately acknowledged, for example, that emergent social facts and the mutually forming connections between agency and structure were identified early on in social theory (Hodgson 2000). It is due to these observations that Comte, who also coined the name 'sociology', placed the discipline at the top of his hierarchy of sciences (Comte 1830) and Durkheim referred to society and social facts as *sui generis* (Durkheim 1912). In this section, we develop the theoretical background of our framework drawing upon the agency/structure debate in social theory. Although ABSS is used in various disciplines, we focus our attention to social theory developed primarily in sociology, due to both its direct relevance to understanding social reality and its effects on the ontological assumptions of the social sciences in general.

2.2 Both agency and social structure are fundamental, yet ambiguous and controversial concepts. When social scientists use the term agency, they often refer to humans' capacity to act. Implicit in this capacity are intentionality and a potential to create impact. Emirbayer & Mische (1998, p. 963), for example, define agency as "a temporally embedded process of social engagement, informed by the past (in its habitual aspect), but also oriented toward the future (as a capacity to imagine alternative possibilities) and toward the present (as a capacity to contextualize past habits and future projects within the contingencies of the moment)." Agency is controversial because it does not readily fit the general order assumed in determinism (Watson 1975) or the stability in structuralism (Ahearn 1999).

2.3 In a similar vein, social structure is a vital concept without a generally agreed definition. We know structure not through what it consists of but through what it is about - regularities, recurrence, order, stability, organisation and so on. We also know about its instances as they emerge from substantive and empirical studies - social roles, culture, institutions, norms, relationships, social networks, class, kinship and so on. Archer (1995) points out that even collectivism, which defends the indispensability of structural factors against methodological individualism, has failed to advance an ontological conception of social structure. She points to the problem of reification in relation to ontological claims in this area. Social structure is difficult to capture without imposing both the real-life existence and generality of theoretical constructs.

2.4 There are, however, indirect constructs of social structure categorising the ways it is conceived in social sciences. Merton (1938), for example, separates goals, which are culturally defined, from means to achieve goals, which are governed by institutions. Radcliffe-Brown (1940) refers to society-wide social relations (e.g., kinship structure), and differentiation of individuals and classes through their social roles. In a similar vein, Blau (1974) refers to differentiation and highlights the link between heterogeneity and social structure, "since social structure is defined by the distinctions people make, explicitly or implicitly, in their role relations" (616). Porpora (1989) identifies four conceptions in the literature: stable or repeated behaviour (associated with individualism), regularities of social facts observed at the level of aggregates (associated with structuralism), systems of relations among social positions (associated with Marxist and post-positivist approaches), and rules and resources (from the structuration approach of Giddens). Martin & Lee (2015) (see also Blau 1974) distinguishes between conceptions of social structure as abstract organisation between macro level categories that constitute the society, and as patterns of concrete, everyday interactions. Bernardi et al. (2006) identify the main divisions of social structure as institutional/cultural and relational/positional.

2.5 Difficult as it may be, defining or categorising agency and structure is not the main challenge in this debate. The core ontological problem is relating them to each other and identifying where one ends and the other begins. Agency and structure appear as contrasting concepts, parts of a dualism. Agency is associated with the impact of individual choice and action. It, thereby, implies change and variety, as well as hope and responsibility. Social structure, on the other hand, is associated with the reproduction and stability of social reality, and relatedly, regularities in observations and constraints on individual choice. At the same time, agency and structure are also embedded in each other. As Marx famously noted, while people make their own history, "they do not make it as they please; they do not make it under self-selected circumstances, but under circumstances existing already, given and transmitted from the past. The tradition of all dead generations weighs like a nightmare on the brains of the living" (Marx 1852).

2.6 A shortcut to deal with this core challenge is treating the unit of analysis at either the macro or the micro level as "ontologically primitive" (Wendt 1987, p.337) by reducing either collectives such as society to aggregates of individuals, or individuals to reproducers of social structure (ibid). Both approaches, roughly representing individualism and structuralism, or in Archer (1996) words, upwards and downwards conflationary theories, have their uses for systematic inquiry of social phenomena. While the first approach makes it possible to infer to the society based on empirical observations of individuals, the second facilitates theorising on properties, parts and theorised functions of a society and the study of population-level dynamics. However, both approaches also have well-known limitations. The first one involves a slippery slope towards empiricism, can fail to capture the fabric of social interactions that cannot be reduced to what is observable at the individual level and

neglects subjective meanings of social realities. The second can lead to mystification of reality in its engagement with unobservable entities and overlook the agency of individuals, at times with overly deterministic undertones (Wendt 1987; Archer 1996). Hence, both approaches cause tensions on numerous axes in the social sciences. Dualisms that encapsulate such tensions include micro/macro, mind/body, objective/subjective and agency/structure (Jackson 1999; Fuchs 2001) and similar tensions can be observed between the search for general theories versus contextual understandings.

2.7 At the same time, some of these concepts are also approached as dualities (instead of dualisms) in which they no longer demarcate separate categories or express contrast. Archer (1996) points out that the interplay between structure and agency yields an alternative. This "non-conflationary" (p.680) form of theorising treats collectives and individuals as analytically separable, but philosophically conjoined (see also Jackson 1999). Giddens (1976), Giddens (1984), for example, in his structuration theory, approaches the constitution of agents and structures as a duality, as opposed to dualism. The basic domain of inquiry "is neither the experience of the individual actor, nor the existence of any form of societal totality, but social practices ordered across space and time" (Giddens 1984, p.2). Structure, in this context, "has no existence independent of the knowledge that agents have about what they do in their day-to-day activity" (p26), it is "both medium and outcome" of the social practices (p25). Bhaskar (1979) offers a similar duality in his critical theory. He argues, however, that people and society are not simply two moments of a process of mutual creation, they are "radically different kinds of thing(s)" (p138). Bhaskar regards society as an "ensemble of structures, practices and conventions" (p 142) and accepts that it would not exist without human activity. Yet, since society always pre-exists individuals, people do not create society, but only reproduce or transform it. Hence, Bhaskar assigns society an existence beyond people's agency.

2.8 In a similar vein, but identifying agency beyond structure, Bourdieu (1980)(see also King 2000) refers to a "fuzzy" logic of practice (p. 87), or "regulated improvisations" (Bourdieu 1972, p.78). Like Marx, Bourdieu argues that material conditions of life (such as those of a class) constitute structures. He, then, links structure to socialisation with habitus: a system of durable dispositions, cognitive and motivating mental structures that people acquire from early ages. Habitus is "a subjective but not individual system of internalized structures" (p86). In a chain of effects, structure produces habitus, habitus produces practices, and practices reproduce regularities in social reality. Yet, according to Bourdieu, social action is not determined by abstract principles or sets of a priori rules. Individuals can improvise upon practical schemes, and negotiate their relations with others through these alterations. Thus, "(e)ven in cases in which the agents' habitus are perfectly harmonized and the interlocking of actions and reactions is totally predictable from outside, uncertainty remains as to the outcome of the interaction as long as the sequence has not been completed" (p.9, 'from outside' emphasised in original).

2.9 In addition to bringing forward the theme of the *interplay* of agency and structure – which was identified early on in social theory - and developing it as explicit ontologies that address the limitations of dualisms, Gidden's structuration theory, Bhaskar's critical realism, and Bourdieu's theory of practice also provide insights on social complexity. From this vantage point, social reality not only involves *systemic*, or *mathematical complexity* that is derived from complexity theory and commonly associated in ABSS literature with nonlinearity, collective dynamics and emergent properties of interdependent social entities, but also *hermeneutical complexity* that accommodates and embeds multiple value systems and ways of reasoning stemming from the richness of human experience and subjective meanings assigned to different aspects of life. In addition, ties between individuals and collectives often build upon common knowledge and assumptions that we learn to forget about. Furthermore, reification of social entities brings abstract concepts into everyday life as real and substantial objects for individuals to face without being able to see them. Further still, social theory involves *reflexive complexity* in that it can affect and become part of common knowledge, make implicit assumptions explicit, challenge or change these assumptions, spark social movements and political change, or strengthen existing structures. It can significantly affect its subject matter, at times causing fault lines in the accumulation of knowledge. It is due to this effect of social theory, for example, that it is hard to consider Marx's work independently of its historical impact.

2.10 According to Archer (1996), since agency and structure are formed through their interactions, understanding the interface between them is "the locus of intensive investigation" (p.680) in non-conflationary approaches (see also systemism in Bunge 2000). In our view, ABSS has an important potential in addressing this locus. While the strengths of ABSS in linking micro and macro levels are well-known, its potential in representing the interplay and interface between agency and structure is not sufficiently explicit nor adequately addressed. Micro/macro and agency/structure are parallel but distinct dualities. Perhaps due to its upbringing in the peripheries of game theory and complexity theory (Macy & Flache 2011), so far, ABSS research has mainly focused on tackling the former. This does not mean that social structure is categorically excluded from ABSS research. On the contrary, common research objectives in ABSS studies include generating patterns, regularities and, at times,

order, bottom up. In addition, some ABSS models represent the effects of structure on agency using norms or rules derived from social settings, usually as *a priori* elements. Hence, elements of the agency/social structure duality are already established and taken for granted in ABSS research. Yet, in the continuous co-evolutions of agency and structure, ABSS models tend to either adopt an *upward looking* approach (Epstein 1999; Tesfatsion 2006; Macy & Flache 2011), and thereby take social structure as *ontologically primitive*, or work with a relatively static snapshot of social structure, not allowing much room for agency. In our view, following insights from social theory and addressing the interplay and interface between agency and social structure more directly can help researchers develop the existing strengths of ABSS and this is one of the motivations for the conceptual anatomy framework that we present in Section 4.

On the Transparency of Agent-based Social Simulation Models

3.1 In the previous section, we developed the theoretical background of our framework and looked at social complexity through the interplay between agency and structure. In this section, we explain how a conceptual framework that helps in making sense of ABSS can be useful. We build on the literature on the epistemology of computer simulations (see also Graebner 2017) and address the transparency of ABSS. Following the original terms used in this literature, we refer to opacity as the opposite of transparency. As well as approaching the subject at an abstract level, we will follow Bourdieu's theory of practice that we reviewed in the previous section, and relate the transparency of ABSS to what we call *research habitus* - practices that are developed in a field of research that are shaped by the structure of the field and available resources. This approach, in particular taking available resources into consideration, allows us to distinguish between the transparency of ABSS under ideal conditions and in practice. It helps to open up various dimensions of transparency/opacity to better locate potential problems and allows us to deconstruct the common criticism that a *computer simulation is a black box* through questions such as *what is opaque, for whom is it opaque* and *which uses* and *purposes are affected by opacity*.

3.2 These examinations yield multiple categories including criteria of transparency, different levels of transparency, objects that need to be made transparent, mediums of transparency and potential sources of opacity. We propose these categories, which are summarised in Tables 1 and 2, not as exhaustive or complete schemes, but as useful distinctions that emerge from our analysis. Our main argument in this section is that neither opacity, nor transparency is intrinsic to ABSS. Not only does ABSS have both strengths and limitations with respect to transparency, but also whether or not an ABSS study appears transparent or ambiguous to a group of agents is contingent upon the level of their engagement, as well as the availability of resources and institutional settings.

3.3 Humphreys (2009, p. 618) defines epistemic opacity formally as: "a process is epistemically opaque relative to cognitive agent X at time t just in case X does not know at t all of the epistemically relevant elements of the process". Putting more emphasis on the cognitive limits of X, he also defines a different version of opacity. In *essentially epistemically opaque* processes, "it is impossible, given the nature of X, for X to know all of the epistemically relevant elements of the process". Humphreys argues that computer simulations are opaque because they replace humans with computers in the research process.

3.4 Recent literature on the epistemic opacity of simulations looks for a more nuanced understanding of the term. Grabner et al. (2019) relates epistemic opacity to issues that have long existed in science such as the division of labour and the use of scientific instruments, which were also considered as black boxes. Duran & Formanek (2018) re-examine Humphreys (2009) notion of epistemic opacity by questioning what *knowing* all relevant elements of a process means. They suggest the following alternative definition: "A process is essentially epistemically opaque to X if and only if it is impossible, given the nature of X, for X to have access to and be able to survey all of the relevant elements of the justification" (p. 650). These two more recent approaches break opacity down to more concrete elements, highlighting multiplicity of researchers, the roles of computers and software, and the degree to which the simulation model and its justifications can be accessed and surveyed.

3.5 Building on these more recent insights, we first distinguish between different actors engaging with simulation models and their purposes in doing so. Millington et al. (2012) raise a similar point and distinguish between the transparency of models for, on one hand, the modeller(s) who went through the iterative process of model building and experimenting, observed many examples of simulated events and learned throughout the process, and on the other, the external audiences. The authors point out that it is much more difficult for non-modellers to follow the logic of how a macro level pattern came to be generated by the given micro level interactions, particularly if they are not given sufficient description of the transformation process in-between (see also Durlauf 2012). This gap in understanding, furthermore, may not be immediately apparent to the modellers, who may take their incremental learnings for granted.

3.6 These distinctions enable us to consider the *black box* in relation to various actors who may have different levels of familiarity with a given model and with ABSS in general. On this basis, we define four levels of transparency. The first level, the *poietic transparency*, refers to the transparency of an ABSS model, experiments and findings for the modeller(s) of the study. Poietic transparency is, thus, both about the final state of the finished, or working model and the modellers' experiences of building it and experimenting with it. The other three levels are about the transparency for people other than the modeller(s) of the study. These are observational, analytical/critical, and participative transparency. They can be defined as: how easy it is for someone other than the modeller(s) to understand and interpret what the model shows (*observational transparency*), comprehend and envisage the main dynamics of the model, so as to be able to assess the strengths and limitations of simulation experiments (*analytical/critical transparency*) and be able to make contributions to the knowledge claims of the model (*participative transparency*).

3.7 Furthermore, by extending Duran & Formanek (2018) abovementioned way of breaking down what knowing epistemologically relevant elements means (accessing and surveying) to these four levels of transparency, we add another distinction between understanding and surveying, and propose the following three criteria for assessing the transparency of ABSS studies: accessibility, comprehensibility and surveyability. With accessibility, we refer to being able to obtain and examine relevant documentation that describes and explains an ABSS model. With comprehensibility, we refer to being able to follow the virtual representation of target phenomena and the causal links between simulated processes. With surveyability, we refer to being able to systematically examine particular aspects or parts of ABSS models, such as their conceptual structure, the way they represent certain interactions, or the entry and exit conditions of agents.

3.8 Thinking about the different actors who engage with ABSS also helps us identify various objects that they engage with. These objects provide answers for questions such as *what exactly is transparent* or *opaque* about ABSS, or to put it differently, *what are the contents of the black box*. They are, therefore, crucial for unpacking the *black box* and starting to address specific limitations. Three themes emerge from our discussion with respect to the contents of the black box: the model as an abstract representation and framing of social phenomena, the code that implements this depiction, and the simulated processes that the code as a whole generates. These three contents of the black box are also made sense of by various actors in relation to, on one hand, the background of the model including its positioning in the existing literature, theoretical reasoning and justifications, and the research question(s), and on the other, the findings of the study and what they mean. Relatedly, in terms of making these objects more transparent, common mediums that are available to researchers are: the presentation of the model as a finished product (including visualisations, interface, notes and explanation on the code), research outputs, in particular model descriptions, and literature reviews that analyse multiple ABSS studies.

Categories of transparency/opacity

Levels of transparency	poietic observational analytical/critical participative
Criteria of transparency	accessibility comprehensibility surveyability
Objects of transparency	visualisations model description code processes
Mediums of transparency	presentation of the model research outputs model descriptions literature reviews

Table 1: Categories of transparency/opacity.

3.9 Distinguishing between different levels of transparency also makes it easier to identify the potential sources of transparency and opacity that we summarise in Table 2. At the level of poietic transparency, a potential strength of ABSS is that it enables further examination of interesting or counterintuitive findings. Referring to experiments with models in general, Morgan (2003) explains that these experiments are developed to find out things that we do not already know, when, for example, different elements are put together, or certain factors are varied. Thus, even though the researchers construct all the elements that produce a change in the model's

behaviour, experiments with models can still surprise them (see also Roos 2016). When this happens, they can go back in an experiment and understand why such results occurred. ABSS, furthermore, involves what Doreian (2002) calls *algorithmic causality* that can be studied with reverse engineering (Manzo 2014). Parallel simulation experiments can be run to acquire a better understanding of causal links in simulated processes by changing parameter values and controlling for one or more factors (Leombruni & Richiardi 2005; Napoletano 2018).

Potential sources of transparency/opacity

Sources of transparency	algorithmic causality relatively simple building blocks more direct representations
Sources of opacity	constructive nature dependency on computers integrative complexity variations in modelling elements

Table 2: Sources of transparency/opacity.

3.10 This does not mean that ABSS researchers cannot make mistakes while building their models or interpreting their findings. Some of the limitations of ABSS are related to models' integrative complexity; their ability to integrate relatively simple elements into complex wholes. Saam (2017) argues that simulations are not opaque due to "sloppy modelling that is poorly understood" but because they are developed for modelling complex phenomena (Saam 2017, p. 80). Similarly, for Lenhard (2017), it is not the step-by-step progress of simulation that is opaque, but the overall process that consists of numerous interrelated steps. These accounts indicate a distinction between the transparency of parts and the opacity of the whole of a simulation. In a similar vein, with respect to software architecture, Newman (2015) points out that even though human errors are expected in software, adopting good software engineering practices (such as using a modular structure) facilitates the reduction, recognition and correction of errors. Hence, although integrative complexity can impede poietic transparency of ABSS models, this risk is not specific to ABSS and there are ways of tackling it.

3.11 ABSS has advantages with respect to the observational transparency. Through representation of agents and their interactions, ABSS models can provide a more direct representation (Gilbert 2008; Frigg & Nguyen 2017) of target phenomena than most other types of social science models. In this regard, they are more transparent than other types of models of social systems (Galan et al. 2009; Polhill 2015) in terms of how easy it is for someone else to understand what a model shows, or at least, is intended to show (Polhill & Gotts 2009). This is particularly the case when the model interface displays well-designed visualisations and users can watch experiment runs.

3.12 When it comes to analytical/critical transparency, ABSS has both strengths and limitations. Lenhard (2017) points out that since compiled codes do not tolerate any ambiguity, they are the most explicit process descriptions used in science. Similarly, Beisbart (2012, p. 409) explain that simulations typically consist of a high number of simple steps. Thus, in theory, 'a sufficiently patient' reviewer could examine the entire simulation without needing a lot of imaginative effort. Referring to practical limitations, however, Lenhard (2017) point out that verifying simulation models is very difficult, especially when the researcher who designs the analytical framework and the programmer who implements the code are different people. The simulation code involves "factors that can go humanly wrong" (Lenhard 2017, p. 12). According to authors, since codes are often not well documented, it can be "maddeningly difficult" (Lenhard 2017, p. 22) to check somebody else's code.

3.13 From a broader perspective, ABSS is a constructive research approach and it allows researchers considerable flexibility in constructing their hypothetical worlds bottom-up. Manzo (2014) points out the similarity between objects in object-oriented programming and agents in ABSS to argue that the basic units of ABSS, the agents, are conceptually empty. Agents can represent individuals, organisations or states, as well as incorporating multiple levels of analysis, heterogeneity and interactions between agents. Moreover, agent's actions can be designed to make rational or boundedly rational decisions, have emotions, beliefs or habits, or follow heuristics (see Balke & Gilbert 2014 for a review). Furthermore, the heterogeneity of agents or the structure of their networks does not have to be fixed; they may evolve over time throughout the simulation (Napoletano 2018). In addition, in exploratory simulation, researchers tend to add additional "knobs and switches" that control factors outside immediate research interests (Bankes et al. 2002, p. 379) for covering broader contexts.

3.14 Although these wide range of flexibilities provide important research opportunities, they may also expand the parameter spaces of models, decrease their analytic tractability (De Marchi & Page 2014) and impede the clarity of causal explanations generated by the study (Macy & Flache 2011). They also mean that a lot of information

needs to be communicated about each model. In line with the constructive nature of ABSS, model descriptions in research outputs are often made in ad hoc ways. Since the space is often limited, furthermore, some assumptions and modelling elements are not fully explained. Hence, the relationship between a model and its description is not one-to-one; a model can be described in different ways and different models can be produced based on a model description (Weisberg 2007, 2013; Graebner 2017). Overall, the constructive nature of ABSS allow researchers to develop original depictions of social phenomena, but it also limits the analytical/critical transparency of ABSS models.

3.15 In addition, ABSS is a research approach that is dependent on computers. Since human minds cannot generate pseudo-random numbers, nor follow the computation process for a high number of agents, the computer is usually a necessary tool for ABSS (Grune-Yanoff & Weirich 2010). Dependency on computers impedes the analytical/critical transparency of ABSS studies because understanding exactly how a given assumption, a scenario or a variable affects simulation experiments can be important to distinguish between the real insights of a study and the obvious outcomes of certain assumptions, or the unidentified effects of others. When a large part of the process is carried out by computers, some human actors may still be able to extrapolate major patterns that are expected to emerge, while others may need to decide whether or not they will take a leap in faith. Once again, this uneasy moment of trusting in the computer is not specific to ABSS and it is not an inevitable problem. If the code of an ABSS model is accessible, it may be scrutinised and systematically analysed by other actors. In practice though, this engagement would depend on skills of these actors, as well as the resources they have to support such a time-consuming engagement.

3.16 With regards to participative transparency, we focus in this section on research fields. At this level, the diversity of modelling elements that stems from the constructive nature of ABSS can be an impeding factor. Even if individual models are kept relatively simple, since the target phenomena are often complex, research fields as a whole can produce a rich collection of modelling ideas and applications. Then, as the field develops further, if each new model uses a different subset of common modelling elements and applies them in slightly different ways, models can quickly lose common grounds. Although there may still be family resemblances between models, variations in multiple dimensions make it difficult to compare like with like, and the field as a whole becomes more opaque. This affects how easily researchers can disseminate their models, compare different models, or assess the level of progress in the field, make sense of findings across different studies, and identify gaps or future research avenues. Since research fields typically progress through collective efforts of groups of researchers (Kuhn 1962) that are co-ordinated via practices of science (Polanyi 1962; Kitcher 1990), improving the transparency of ABSS models is crucial to increase their use and impact (Lorscheid et al. 2012; Sohl & Claggett 2013; Müller et al. 2014). This is especially important given the disciplinary diversity of the ABSS modelling community.

A Conceptual Framework for Agent-based Social Simulation

4.1 In previous sections, we built a link between social theory and ABSS, and developed the theoretical background through the agency/structuration debate. We have also addressed the transparency of ABSS, unpacked the black box and evaluated the strengths and limitations of ABSS. In this section, we will take a further step and introduce a general framework that helps to make sense of ABSS models and improve their transparency. Since our aim is facilitating sensemaking, in designing the framework we did not start from the mathematical properties of complexity, nor introduce an overly technical schema. Instead, we aimed to keep the framework simple, yet as comprehensive as possible, providing rich information about models in a succinct way. We, therefore, aimed to identify conceptual elements that are intuitive for thinking about both social reality and ABSS models. Regarding the former, we referred to social theory, looking for insights on how social reality is made sense of. Regarding the latter, we looked for conceptual elements in descriptions of agent-based models. The framework we propose has five elements: agents, environment, actions and interactions, social structure and temporality.

4.2 These conceptual elements are not new. Macal & North (2006) step-by-step tutorial for building agent-based models distinguishes between building the agents, the environment and the agents' behaviour (methods) and interactions. Likewise, in the context of describing agent-based models, Bandini et al. (2009) identify these concepts (environment, agents, interactions) as elements of a basic model. We added two more elements – social structure and temporality - that are covered in ABSS models (albeit implicitly) and that are important for building a more complete and coherent picture. We have added social structure to cover how agents are connected to each other and the ways in which these connections play out in social reality in a way to create some form of order as opposed to randomness. Similarly, we have included temporality in the framework to reflect the way(s) time is represented and the processes generated by the model.

4.3 In relation to social theory, our framework captures the fundamental dynamics between agency and structure, as well as their interplay through actions and interactions embedded in place and time. We have covered agency and structure in Section 2. In this section, we will provide a brief review of how actions and interactions, place and time are approached in social theory, and how they are complementary to each other in understanding social reality.

4.4 Actions and interactions captured interest in social theory both as some of the basic elements that researchers can empirically observe, and as the link between agency and social structure. Regarding the former, Weber (1922) defined sociology as the science that aims to "interpret the meaning of social action and thereby give a casual explanation of the way in which the action proceeds and the effects which it produces" (Weber 1922, p. 7). Action, in this sense, is behaviour that is (subjectively) meaningful to the agent(s), and, in social action, this meaning involves a relation to other people's behaviour in a way to shape the action. Others including Parsons (1937) interpreted purposefulness of action in a similar way to rationality in economics. While Weber emphasised that there can be no objective assessment of the meanings assigned to actions by agents in an empirical science, Parsons distinguished between the actors' subjective meanings and the scientist's objective observation. Regarding the latter, as briefly outlined in Section 2, in "non-conflationary" (Archer 1996) approaches, interactions both shape and are shaped by social structure.

4.5 Non-conflationary approaches also recognise that social reality is embedded in particular places and time (see, for example, Giddens 1981; Bourdieu 1972). Regarding place, Tuan (1977), argued that abstract space is organised into meaningful and distinguishable places, as people get to know certain locations and assign value to them through experiences. Places are important for the conception of the self, so much so that for Relph (1976), to be human "is to live in a world that is filled with significant places: to be human is to have and know your place" (Relph 1976, p. 1). Places can affect people and their agency by disciplining everyday life (Foucault 1978), and providing access to, or excluding people from various activities. Assigning women's place as the home, for example, has a part in their subordination by blocking their access to the reproduction of power, and in social control over women by limiting their mobility (Gieryn 2000). As it is familiar to ABSS researchers (see Hegselmann 2017), places may segregate categories of people (see Hamnett 2001 for a review) including different races, ethnicities and classes (Gieryn 2000). Places can also materialise a symbolic logic that reinforces these diverse forms of structuring (Bourdieu 1972). In short, places embody social structure in a way to surround us and so, social space is ordered, albeit with a local logic that may not be generalisable or fully accessible to outsiders.

4.6 In social theory, time is often addressed in relation to agency, structure and their interplay. Parsons (1937) points out that "an act is always a process in time" as an "end always implies a future reference" (Parsons 1937, p. 45). Thus, agents assign meaning to their behaviour through temporal reasoning. Durkheim (1912) highlights that time is structured collectively. This structuring enables individuals to perceive and make sense of time as well as co-ordinating with others. Foucault (1978) approaches the same process from the aspect of power. He points out that the time-table, a modality of monastic communities that spread to military, schools and work places, enables the control of activities by establishing common rhythms and regulating their repetition.

4.7 Overall, our framework provides a link between conceptual elements of ABSS and some of the important dimensions of social reality. Of course, ABSS has its own approach and habitus in relation to these matters. We are not claiming there is an exact match between the diverse meta-theoretical considerations raised in social theory and common representations in ABSS. Instead, we expect that our framework will facilitate relatively painless transfer of ideas from social theory to ABSS studies, and equally, further theorisation of some of these issues through ABSS models.

4.8 One of the advantages of the framework is its simplicity. We expect that its intuitiveness for thinking about both the conceptual structure of ABSS and meta-theoretical considerations in social science can facilitate model development and enhance interdisciplinary and collaborative work. At the same time, the elements of the framework are understood in various ways in different fields. In this respect, we are not claiming to bridge, or provide a common vocabulary for ABSS and social theory, but rather entry points for further exploration and cross-fertilisation. Relatedly, as we will discuss in the following sub-sections, the main limitation of our framework is that its elements are not strictly defined, mutually exclusive concepts. As such, the framework we propose is not a detailed guide, but a tool that requires further effort and attention in application to substantive topics. Although this is a limitation of the framework, we expect that these efforts would be worthwhile in advancing theoretical depth and coherence of models. In the remainder of this section, we will explain the five elements in the framework in more detail. For each element, we will briefly refer to existing approaches in ABSS, point out connections with the other elements in the framework, and explain how we conceive the distinctions between them, although we expect such distinctions to vary between researchers and research fields.

Agents

4.9 As the name implies, agents are at the core of ABSS. In the existing literature, agents are described in terms of properties such as autonomy, heterogeneity, mobility, memory, perception of and reaction to surroundings, interactivity, (bounded) rationality, and learning and adaptation (see, for example, Crooks & Heppenstall 2012). Such properties allow agency to be situated in an interdependent decision making (also known as strategic, or game-theoretic in economics) context created by a population of self-interested (albeit boundedly rational) entities that have internal models for how the other entities will behave (Axtell 2005).

4.10 While agents that are created through instantiation of classes in the code are explicit and are often included in model descriptions, ABSS can also entail more implicit agents (e.g., agents like the state or nature that are represented with a single global variable), or agent collectives (e.g., firms, organisations) that consist of a set of individual entities (e.g., employees, managers) that are also modelled as agents. The first element of the conceptual framework covers what agents in an ABSS model represent, a general understanding of their aims and intentions, their capacity to act and the impact they can have over the other elements of the framework.

Social structure

4.11 The second element of the framework is social structure. The role of social structure in the existing ABSS literature is not as explicit as that of agency. That said, it is covered in (at least) two ways. Firstly, parts or instances of structure are represented in ABSS models, often through simulated relationships (e.g., social networks) or rules (e.g., institutions, norms) that shape agents' behaviour. Secondly, ABSS covers social structure as an emergent property of interactions. The knowledge ABSS models create in this context is relational, shedding light on how individuals relate to and become part of collectives such as the society, and how these relationships, with their shared assumptions and conduct, impact upon individuals.

4.12 There are ontological links between social structure and the other elements of the framework. Although social structure would not meaningfully exist if there were no agents, it also has a distinct nature as it is not exactly contained in any particular individual (see Bhaskar 1979 arguments reviewed in Section 2). Thus, from the perspectives of individual agents, social structure is largely (albeit not completely) beyond their own agency especially in the short run. We distinguish social structure from agency and environment through its distributed (among agents) and relational (between agents) nature. In terms of the main types or examples of social structure, while the categories mentioned above are all useful to give a good indication of the broad scope and variety of structures, in our view, Bernardi et al. (2006)(see Section 2) categories (institutional/cultural and relational/positional) best match the ways social structure is represented in ABSS models. This may be extended with Blau (1974)(see Section 2) differentiation perspective, which may be useful to cover systemic differences between groups and socially constructed aspects of heterogeneity in ABSS models. This would lead to three main categories of social structure: institutions, relationships and systemic differences.

Environment

4.13 The environment that agents are placed in and interact with is the third element of the framework. Once again, ABSS offers high level of flexibility and supports virtual environments at different levels of detail. Some models aim for geographically realistic environments with elements such as resources, barriers and special locations like home, hometown, or a marketplace. Other models represent material or social settings via simple sets of variables, matrices and functions. Agents' locations in simulated space can have metaphorical meanings as well. The distances between agents, for example, can be used to represent differences in social class, opinions, or ideology (De Marchi & Page 2014). In a similar vein, meanings can be assigned to movement. Fitness landscapes, for example, represent possible solutions to a set of problems and moving on this landscape can represent a research or problem solving process. These diverse representations imply that ABSS can accommodate the way space, places and material conditions of life are thought of in social theory.

4.14 Agency and environment are often closely linked in ABSS models. Individual agents may face different environmental settings, or perceive the environment differently from each other (Seth 2002). Furthermore, agents can change the environment by, for example, accumulating or depleting resources, building structures, or changing the population density of certain areas through their movement and, thus, interact through the simulated environment (Bandini et al. 2009; Argente et al. 2013).

4.15 Within the conceptual framework, environment is relatively straightforward to identify at a particular point in simulated time. It is the virtual backdrop that is external to and surrounding the agents. From a long-term

perspective, however, it may be necessary to consider if and how environment, social structure and agency co-evolve. Furthermore, when one considers the environment of an individual agent, other individuals, and so the social structure can be seen as part of the agent's social environment. That being said, regarding social structure as yet another aspect of agents' environment flattens important considerations in social science and overlooks the hermeneutical complexity (see Section 2) of social structure. We, therefore, approach social structure and environment as separate elements of the framework and for simplicity, do not consider other agents as part of an agent's environment.

Actions and interactions

4.16 The fourth element of the framework is the actions and interactions of agents. It is through agent actions and interactions that an ABSS model gains its dynamic feature and produces a story that resembles real life. Agents' actions include, for example, cognitive processes such as receiving and processing information, making calculations, building expectations for the future, and making decisions. Actions also include movement in physical as well as other spaces. Agents' interactions can be with each other (e.g., communication, market exchanges), with other classes of agents, or with the environment (e.g., consumption, production).

4.17 Actions and interactions of agents are closely linked with other elements in our framework. For example, simulated structure such as norms and institutions can shape the ways in which agents interact. Furthermore, both the environment and social structure can determine who will interact with whom. In some models, agents interact with others in their immediate surroundings. In others, they interact with those that are in their social networks. In yet other models, there are explicit procedures for search and matching that may involve agents specifically looking for agents with certain properties. The link between agency and actions and interactions is even stronger; the latter reflects and displays the former.

4.18 We propose the following distinction between agency, and actions and interactions. As described in sub-section 4.1, we regard agency as the capacity of agents to act including their cognitive, productive and mobility-related capabilities. Actions and interactions, however, are about how these capacities are used in contexts generated by the model. They are, therefore, more practical and specific compared to representations of agency. Both constraints imposed by the local environment and social structure, and the effects of stochasticity can lead to varied actions and interactions by agents with the same or similar capacities.

Temporality

4.19 The final element in the conceptual framework is temporality. In the ABSS literature, simulated time can be implemented in a period-oriented or event-oriented way, or with a combination of both (see also O'Sullivan & Perry 2013; Meyer 2015). In period-oriented ABSS models, the simulation code involves a series of actions and interactions that are thought to happen during a time period such as a day, or a month, and these series are executed many times in the same order, often with varying outcomes based on predefined conditions, to create a sense of the flow of time. In event-oriented models, on the other hand, simulated time advances from the occurrence of one event to the next and the state of the simulated system is assumed to be constant in between these events. By skipping inactive points in simulated time, the event-oriented approach achieves both higher efficiency and greater accuracy in terms of capturing specific moments in which significant events occur (Meyer 2015). Most ABSS models employ the period-oriented approach (ibid) and we think of temporality with a period-oriented approach in mind. At the same time, clarifying the way time flows and reflecting on the processes that are generated can benefit event-oriented models as well.

4.20 We see temporality as the ways in which time and history are conceptualised, simulated and studied in ABSS models. Thus, temporality has two sides, simulated time and history, both of which are important for building a rich understanding of an ABSS. Among the transparency objects that we identified in Section 3, temporality is related to both the model and the simulated processes and so reflecting on the temporality of a model can be beneficial for improving the transparency of both of these objects.

4.21 Time is conceptualised and simulated in ABSS in a way that suits the target phenomena as part of the model building process. Clarifying the way(s) time is represented helps researchers to understand the mechanics and rhythms in a model. History, on the other hand, is about reflecting on the events and developments occurring within the flow of simulated time. It indicates how consecutive periods are connected to each other and what evolves or can evolve over time out of such connections. In addition to continuous dynamics that link periods, there can be developments that stand out from the mundane such as vital events, or state changes. Such

historical developments can produce branched histories, providing important insights about real-life complex phenomena [1]. Reflections on history help to clarify what the model is intended and/or likely to produce. This is different from reporting experiment results. While experimental results depict what was observed in particular simulation settings, history is about the dynamic properties and workings of the model in general.

4.22 In addition, historical elements of an ABSS can be analysed reflexively, comparing what researchers expected to find with the simulation results. We call this side of temporality historicity. This analysis is particularly useful for studying emergent social phenomena. Emergence in this context usually refers to unexpected and/or counter intuitive societal outcomes of individual or micro-level interactions. ABSS models of social complexity have inherent strengths in understanding emergent phenomena. Similarly, ABSS models are well suited for possibility proofs that show that alternative simulated realities can emerge from identical or similar initial conditions. In both cases, once the effect is observed, researchers can explore the mechanisms that produce these results by digging into the model, running additional experiments, studying the model in parts or thinking again about the connections between its elements (see Section 3). Ironically, however, once these emergent effects are understood, it may be unclear to the reader whether the model was intentionally constructed to produce them. It is, thus, important to specify whether or not an effect was *a priori* unexpected [2]. Reflecting on the historicity of ABSS models can be useful to provide a clear and credible account of the study and its background, particularly if researchers prepare two sets of notes, before and after experimentation, on the major temporal dynamics of their models.

Potential Uses of the Framework

5.1 In this section, we will discuss potential uses of the conceptual framework for improving the transparency of ABSS. We will, therefore, build upon Section 3 and relate the main uses of the framework to the transparency categories we identified. In three sub-sections, we will explain how the framework can be used for model development and teaching, model specification and literature reviews.

Model development and teaching: Improving poietic transparency

5.2 ABSS can create complex simulated worlds. Throughout the development of an ABSS model, researchers may integrate well-established theories, their own conceptual frameworks and some improvisations that fill in any gaps and make the model work. Although model development sometimes progresses naturally and effortlessly, this is not always the case. For less experienced modellers, those who are tackling a new subject and those who are collaborating in an interdisciplinary study, getting a strong grip of what the model should be like can be a daunting and confusing task. We expect that the framework we propose will be useful for thinking about different aspects of complex social phenomena (e.g., the kind of agency various actors have, their impact on the environment, or evolving social structures) and for designing a simulated world in parts.

5.3 We suggest that the conceptual framework can be helpful for making sense of both what ABSS in general involves and how it can be used in relation to particular substantive topics and research questions. A short description of the envisaged model in terms of its five conceptual elements can be a good starting point for designing the model, as well as communicating ideas with collaborators. Thinking about one of the elements of the framework at a time can make model development more manageable. In addition, by focusing on the elements of the framework that are most relevant to the research question in hand, researchers can refine their approach. The framework can also help researchers in grounding their models in social theory. Furthermore, since different dimensions of social reality are often interdependent, clarifying the research approach for the five elements can help novice researchers and non-modeller collaborators to frame their approach and avoid circular thinking, while also recognising the potential limitations of their approach and future research trajectories. In the later stages of model building and experimentation, exploring the temporality of the model can help researchers make sense of simulated processes. As mentioned in Section 4, researchers can identify and justify emergent findings in a better way if they reflect on temporal dynamics of their models before and after experimentation.

Model description: Linking mediums and objects of transparency

5.4 The model description section in research outputs is probably the most important medium that researchers can use to improve the transparency of their work. An effective model description helps readers understand

the main dynamics of a model and assess its strengths and limitations. They also guide researchers in building similar or comparable models. Model description, therefore, is closely related to both the third and fourth types of transparency that we identified in Section 3, namely critical/analytical and participative transparency.

5.5 While providing clear and information-rich model descriptions is important, there is a trade-off between providing more details and being able to elucidate essential ideas succinctly. A document describing and justifying all entities, variables and assumptions of a large-scale ABSS model may not be of much practical value, because such a text would be almost as time-consuming for readers to study as the code itself. In this regard, "the computer code itself is often not that far from being one of the best descriptions" of the model (Galan et al. 2009). Given the premium on space in research papers, it is likely that some elements of the model are explained in more detail than others. Furthermore, since entities in ABSS models are often connected to each other in multiple ways, model descriptions tend to contain chains or circles of cross-references that authors may organise in various ways. Thus, models with similar elements can be described differently (see also Section 3). As such, not only the modelling components, but also the narratives that describe them involve flexibility.

5.6 One way to improve the effectiveness of model descriptions is to apply a framework. As mentioned in the Introduction, the most popular framework is Overview, Design concepts and Details (ODD) protocol (Grimm et al. 2006, 2010, 2017). In the ODD framework, modelling entities, processes, and the purpose of the study are introduced in the Overview section. Then, in the Design section, the model is discussed according to a list of concepts (e.g. emergence, adaptation) that are derived from the complex adaptive systems literature (Railsback 2001). Finally, the implementation of the model, including the experimental settings and inputs, are specified in the Details section.

5.7 There have been some criticisms of ODD. Firstly, as noted in an update of ODD (Polhill 2010), not all of the concepts listed under the Design section are relevant to all models. More importantly, the framework does not aim to produce coherent categories of design issues. For example, the list includes emergence, which is often considered to be the counterintuitive outcome of micro-level interactions rather than an element of model design. The list also includes a mix of some specific capabilities of agents (e.g., adaptation, learning, sensing, observing, predicting), while omitting others (e.g., mobility and production), a more general category of agent behaviour (interaction) and a mathematical aspect of the model (stochasticity).

5.8 We took a different approach. Instead of starting from listing the properties of complex systems that modellers in general might be interested in, we aimed to facilitate making sense of ABSS with intuitive categories that are compatible with those that researchers are used to when they are theorising about social phenomena. Furthermore, building on some of the categories that we identified in Section 3, we aimed to facilitate a strong connection between model descriptions and two of the main objects of transparency, namely, the model and the simulated processes. This differs from ODD, which not only covers the description of the model but also its purpose, and the initialisation of simulation experiments.

5.9 While we appreciate the role of research purpose in model development, we see it as part of the priors, or background of the model. The purpose of a study and the research questions it addresses are usually developed through an engagement with the existing literature and theoretical frameworks, which also impact upon the scope, components and main dynamics of models. Thus, the purpose is often already explained in the introduction and literature review sections of research outputs. Similarly, although the description of experimental settings is very important for clarifying knowledge claims in a research paper, it is helpful in explaining how the model is used rather than the model itself. Since the space available for model description is often scarce and the content is already rich, instead of expanding model description to some of the other elements of the study that are prior or posterior to the model, we focus on the abovementioned three objects. We, nevertheless, encourage researchers who use our framework to reflect on the background of the model, clarifying its purpose and theoretical approach and present experimental settings clearly in their research outputs.

5.10 To facilitate the use of the framework for model descriptions, it is shown in a checklist format in Table 3 in the Appendix. The checklist includes some sub-categories of the five elements and short definitions. We envisage that this list can be used as a starting point for describing a broad range of social simulation models, although we recognise the difficulty of defining such a structure a priori. Models in some fields may require additional distinctions and some items in the list may be more useful than others. The checklist, therefore, should be taken as a flexible, dynamic and evolving construct rather than a strict format. The checklist also has two optional sections where researchers can summarise information about the background of the model and experimental settings. These two optional sections may also be useful to produce a standalone research report in a format that is parallel to but more concise than a full research output such as a journal article.

Anatomical reviews: Making sense of a body of research

5.11 Literature reviews have a crucial role in enhancing the usefulness and impact of research fields. They help researchers identify common ideas, arguments and assumptions, recognise the strengths and weaknesses of existing studies and shed light on future research avenues. In this regard, thorough literature reviews can improve both critical/analytical and participative transparency. In this sub-section, we discuss how using the framework for conducting *anatomical reviews* can improve the transparency of models. We use the metaphor of anatomy to describe the conceptual structure of models. We expect that similarities and differences between models can be clarified by reference to a general conceptual anatomy in a manner similar to comparative anatomy studies.

5.12 As mentioned in previous sections, the flexibility of AB modelling may lead to a diverse range of models with just family resemblances. Even though there will be common modelling approaches in the field, each model contains a different subset of these commonalities and applies them in slightly different ways. This is particularly the case when there are many large-scale models in a growing research field such as studies of common pool resources, agent-based macroeconomics, and city simulations. While critical reviews of modelling approaches and elements can help improve the transparency of these research fields as a whole, conducting such informative reviews is not a simple task and not done often enough. Even if research outputs provide detailed information about models, it is hard for those who are carrying out a literature review to organise and make sense of this information without using a coherent framework (see also Bithell & Edmonds 2020).

5.13 We expect that the conceptual framework can be of use to reduce this problem. Since our aim in building it was finding an intuitive, coherent and succinct description of what ABSS is, the resulting framework can be useful in identifying common *anatomies* of ABSS models. The initial focus in this process may be on identifying similarities between models. Through similarities, reviewers and readers can identify the common *anatomy*, the generic structure of ABSS models in a field. This analysis can also help the identification of baseline models, the simplest applications of common modelling approaches in a field. After identifying common anatomies and possibly baseline models, reviewers can undertake comparison of differences. This analysis can outline the level of diversity in the field as well as bringing to light good modelling ideas that advance specific parts of the state-of-art, which might otherwise remain hidden.

5.14 Anatomical reviews can also enhance critical/analytical transparency by showing common limitations. Relatedly, they can improve participatory transparency by shedding light on new research trajectories. Similarly, identification of baseline models can help new researchers to enter the field. In term of poietic transparency, anatomical reviews can help researchers make more explicit decisions about their modelling components. By highlighting the common anatomy of models in the field, anatomical reviews can help researchers decide whether they should diverge from the existing models and develop innovative representations, or exploit the advantages of standardisation in the field while they are designing modelling components.

Conclusions

6.1 In this paper, we examined the black box of ABSS in several ways. Firstly, we analysed what ABSS is from a conceptual point of view. We tackled questions such as what the conceptual structure of ABSS is and what it represents. In order to answer these questions, we looked at descriptions of both ABSS and its target: social reality. These comparative analyses yielded a simple framework or conceptual anatomy of ABSS, which can be useful for people with different levels of engagement with this research approach to make sense of it and what it does. The analyses also shed light on the unfulfilled potential of ABSS research in representing social phenomena in ways that are explicitly grounded in social theory. In particular, we highlighted the potential of ABSS to represent the interplay and interface between agency and structure.

6.2 Secondly, by building upon the rapidly developing epistemology of computer simulation, we unpacked the black box of ABSS. Relating arguments in this literature to ABSS research habitus, we examined questions such as what exactly is opaque about ABSS, to whom it is opaque and in what ways. We identified themes emerging in six categories of transparency, which helped to identify some of the strengths and limitations of ABSS. We argued that opacity is not intrinsic to ABSS because ultimately both its code and the processes it generates can be accessible, comprehensible and surveyable. Yet, transparency is not intrinsic to ABSS either, because it can take a long time to study and understand code and the processes of a highly parameterised ABSS, possibly longer than researchers can afford to spend on others' work. This perspective allows ABSS to be seen not necessarily as a black box for all audiences, but more transparent for some who engage with, access to and study them and more opaque for others. It also implies that paths that go in and out of this box can be maintained through

research practices. We closed the loop by formulating potential uses of the conceptual framework within the ABSS habitus for improving the transparency of models.

6.3 It emerges from these analyses that the core value of ABSS and the epistemological concerns about it are conceptually co-located at the limits of human cognition. In our view, this is where one black box (ABSS) is prying open another, larger black box (dualities including micro/macro and agency/structure). ABSS is a valuable research approach because it enables us to construct alternative representations of subjective social entities, build complex virtual realities out of seemingly simple, mundane elements, extrapolate outcomes of numerous interactions, and incorporate stochasticity in ways that could not be performed without computer simulations. On the other hand, ABSS may not be seen as reliable because of the subjective representations it entails, the complex realities it creates and the computer-generated processes that it depends on.

6.4 We expect that reflecting on the elements of the conceptual anatomy framework will facilitate better grounding of ABSS models in ontological considerations, and, in turn, help ABSS studies to provide insights for social theory. In this, we do not imply that ABSS can sufficiently address all meta-theoretical angles relating to agency and structure, or the embeddedness of social reality in time and place, but it can help researchers make contributions to theory building and experimentation. Along with these uses and advantages, the framework we present in this paper also has some limitations. As mentioned in previous sections, the elements of the framework are not clear-cut, mutually exclusive categories. Although this necessitates further analytical effort, we expect that these efforts would be worthwhile in advancing the theoretical depth and coherence of ABSS models. In addition, an *a priori* framework such as ours may not fit all research fields and modelling approaches. Thus, we do not suggest the framework should be used as a strict construct or model description procedure. Instead, we provide it as a useful starting point and one of the tools in the toolbox available to social simulation researchers.

Appendix

Background of the model	
Sub-categories	**Suggestions**
Purpose	Clarify why the model was built including research questions and objectives
Theoretical Background	Provide a brief overview of the theoretical background of the main assumptions of the model
Model development	Provide brief reflections on the process of model development. Outline components taken from other models (if any) and new modelling ideas.
1.Agents	
Sub-categories	**Suggestions**
a. Types of agents	Explain different agent types, distinguishing between explicit and implicit agents, and multi-level conceptions of agents (if any). Clarify the number of agents in each category.
b. Heterogeneity	Explain within-class heterogeneity in terms of attributes and important state variables.
c. Intentions	If not immediately intuitive, explain aims and objectives of each type of agent.
d. Capabilities	Comment on general capability levels of agents. Explain capabilities of agents. This includes, but not limited to, cognitive abilities (e.g. perception, strategic reasoning, learning, mobility, production and consumption.
2. Environment	
Sub-categories	**Suggestions**
Physical environment	If there is a simulated physical (natural and built) environment, explain what it represents, its elements and properties. Clarify the level of detail/abstraction.
Metaphorical environment	If space is used metaphorically, explain what distance and locations stand for.

Abstract environment	If there is no explicit environment, but the properties of the physical or social environment are reflected in other entities (e.g., payoff structures, implicit agents, black-boxed processes) explain these entities.
3. Social Structure **Sub-categories**	**Suggestions**
a. Institutions	Explain elements of social structure that govern, shape or impact upon agents' behaviour including shared habits, institutions, norms and social practices. Clarify if they are set a priori or they emerge from interactions between agents.
b. Relationships	State the number of different relationships and their social, economic or political contexts (if any). Clarify if relationships facilitate interactions such as exchanges, access to resources or information. If relationships are expressed in social networks, explain the properties of these networks, the way they are built and how they evolve. Explain if empirical network data is used.
c. Systematic differences	Reflect on distributions of heterogeneous attributes and clarify aspects that relate to social structure. Explain factors that may affect interactions if some agents are treated differently than others.
4. Actions and Interactions	
Sub-categories	**Suggestions**
a. Cognition	Explain the cognitive tasks (e.g., utility assessment and comparisons, expectation building) agents perform.
b. Mobility	If agents move in space, explain how.
c. Production and consumption	If agents can transform other entities, explain how.
5. Temporality	
Sub-categories	**Suggestions**
Before simulation experiments	
a. Time	Explain general conception of time. Reflect on how consecutive periods are connected to each other through common events and changes in state variables.
b. History	Explain the main dynamics and likely historical paths.
After simulation experiments	
c. Chronicles	Provide an account of important events that relate to emergent findings and a comparison with a priori notes on histories highlighting findings that experiments help to reveal.
Experiment Notes	
Sub-categories	**Suggestions**
Verification	Describe the steps taken to verify that the ABSS correctly implements the intended model
Experiment design	Summarise the experiment design, outlining scenarios (if any), experiment/control groups (if any), or other bases of comparison.
Parameter settings	Explain how main parameters were set, if and how they were calibrated.
Key findings	Present a brief overview of key findings and their implications
Validity	Explain if and how the empirical validity of the model is tested and robustness of findings is analysed.

Table 3: Model description categories based on the conceptual anatomy framework.

Notes

[1]Peuquet (2005)(see also Crooks & Heppenstall 2012) categories of simulated events can be useful for reflecting on different forms of change across time. The author distinguishes between four types of events based on their temporality: continuous events occur throughout time, majorative events occur most of the time, sporadic events occur from time to time and unique events occur once.

[2]Although researchers can contribute to knowledge in both ways - by demonstrating an a priori statement and exploring unexpected outcomes of a complex system - the way an ABSS model is used in these knowledge creation paths is different. In the former, the ABSS model works as an exhibit or visualisation of a theoretical statement. In the latter, it works as a laboratory enabling observations and discoveries.

References

Ahearn, L. M. (1999). Agency. *Journal of Linguistic Anthropology*, *9*(1–2), 12–15

Ancona, D. (2012). Sensemaking: Framing and acting in the unknown. In S. A. Snook (Ed.), *The Handbook for Teaching Leadership: Knowing, Doing, and Being*, (pp. 3–19). Los Angeles, LA: SAGE

Archer, M. (1995). *Realist Social Theory: The Morphogenetic Approach*. Cambridge: Cambridge University Press

Archer, M. (1996). Social integration and system integration: Developing the distinction. *Sociology*, *30*(4), 679–89

Argente, E., Boissier, O., Carrascosa, C., Fornara, N., McBurney, P., Noriega, P., Ricci, A., Sabater-Mir, J., Schumacher, M. I., Tampitsikas, C., Taveter, K., Vizzari, G. & Vouros, G. (2013). The role of the environment in agreement technologies. *Artificial Intelligence Review*, *39*, 21–38

Arthur, W. B. (2005). Out-of-equilibrium economics and agent-based modeling. International Institute for Applied Systems Analysis (IIASA), 2005. Available at: `www.jstor.org/stable/resrep15743`. Accessed 28 Feb. 2020

Axtell, R. (2005). The complexity of exchange. *The Economic Journal*, *115*(504), 193–210

Balke, T. & Gilbert, N. (2014). How do agents make decisions? *A Survey, Journal of Artificial Societies and Social Simulation*, *17*(4), 13

Bandini, S., Manzoni, S. & Vizzari, G. (2009). Agent based modeling and simulation: An informatics perspective. *Journal of Artificial Societies and Social Simulation*, *12*(4), 4

Bankes, S., Lempert, R. & Popper, S. (2002). Making computational social science effective epistemology, methodology, and technology. *Social Science Computer Review*, *20*(4), 377–388

Beisbart, C. (2012). How can computer simulations produce new knowledge? *European Journal for Philosophy of Science*, *2*(3), 395–434

Bernardi, F., Gonzalez, J. J. & Requena, M. (2006). The sociology of social structure. In C. D. Bryant & D. L. Peck (Eds.), *21st Century Sociology: A Reference Handbook*, (pp. 162–170). Newbury: Sage

Bhaskar, R. (1979). *The Possibility of Naturalism: A Philosophical Critique of the Contemporary Human Sciences*. London: Routledge

Bithell, M. & Edmonds, B. (2020). The systematic comparison of agent-based policy models - it's time we got our act together! Review of Artificial Societies and Social Simulation, 11th May 2021.Available at: `https://rofasss.org/2021/05/11/SystComp/`

Blau, P. M. (1974). Presidential address: Parameters of social structure. *American Sociological Review*, *39*(5), 615–635

Bourdieu, P. (1972). *Outline of a Theory of Practice*. Cambridge: Cambridge University Press

Bourdieu, P. (1980). *The Logic of Practice*. Cambridge: Polity Press

Bunge, M. (2000). Systemism: The alternative to individualism and holism. *The Journal of Socio-Economics*, *29*(2), 147–157

Comte, A. (1830). *Positive Philosophy*. Kitchener, Canada: Batoche Books

Crooks, A. T. & Heppenstall, A. J. (2012). Introduction to agent-based modelling. In A. J. Heppenstall, A. T. Crooks, L. M. See & M. Batty (Eds.), *Agent-Based Models of Geographical Systems*, (pp. 85–108). Berlin Heidelberg: Springer

De Marchi, S. & Page, S. E. (2014). Agent-based models. *Annual Review of Political Science*, *17*, 1–20

Delli Gatti, D., Gaffeo, E. & Gallegati, M. (2010). Complex agent-based macroeconomics: A manifesto for a new paradigm. *Journal of Economic Interaction and Coordination*, *5*(2), 111–135

Doreian, P. (2002). Event sequences as generators of social network evolution. *Social Networks*, *24*(2), 93–119

Duran, J. M. & Formanek, N. (2018). Grounds for trust: Essential epistemic opacity and computational reliabilism. *Minds and Machines*, *28*, 645–665

Durkheim, E. (1912). *The Elementary Forms of the Religious Life*. London: George Allen & Unwin Ltd

Durlauf, S. N. (2012). Complexity, economics and public policy. *Politics, Philosophy and Economics*, *11*(1), 45–75

Edmonds, B. & Meyer, R. (Eds.) (2013). *Simulating Social Complexity: A Handbook (Understanding Complex Systems)*. Berlin Heidelberg: Springer

Emirbayer, M. & Mische, A. (1998). What is agency? *American Journal of Sociology*, *103*(4), 962–1023

Epstein, J. M. (1999). Agent-based computational models and generative social science. *Complexity*, *4*(5), 41–60

Foucault, M. (1978). *Discipline and Punish: The Birth of the Prison*. New York, NY: Vintage Books

Frigg, R. & Nguyen, J. (2017). Models and representation. In L. Magnani & T. Bertolotti (Eds.), *Springer Handbook of Model-Based Science*, (pp. 49–102). Berlin Heidelberg: Springer

Fuchs, S. (2001). Beyond agency. *Sociological Theory*, *19*(1), 24–40

Gaffeo, E., Delli Gatti, D., Desiderio, S. & Gallegati, M. (2008). Adaptive microfoundations for emergent macroeconomics. *Eastern Economic Journal*, *34*(4), 441–463

Galan, J. M., Izquierdo, L. R., Izquierdo, S. S., Santos, J. I., del Olmo, R., López-Paredes, A. & Edmonds, B. (2009). Errors and artefacts in agent-based modelling. *Journal of Artificial Societies and Social Simulation*, *12*(1), 1

Giddens, A. (1976). *New Rules of Sociological Method*. Cambridge: Polity Press

Giddens, A. (1981). *A Contemporary Critique of Historical Materialism*. Stanford, CA: Stanford University Press

Giddens, A. (1984). *The Constitution of Society: Outline of the Theory of Structuration*. Cambridge: Polity Press

Gieryn, T. (2000). A space for place in sociology. *Annual Review of Sociology*, *26*, 463–496

Gilbert, N. (2008). *Agent-Based Models*. London: Sage

Graebner, C. (2017). How to relate models to reality? An epistemological framework for the validation and verification of computational models. *Journal of Artificial Societies and Social Simulation*, *21*(3), 8

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S. K., Huse, G., Huth, A., Jepsen, J. U., Jø rgensen, C., Mooij, W. M., Müller, B., Pe'er, G., Piou, C., Railsback, S. F., Robbins, A. M., Robbins, M. M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman, R. A., Vabø, R., Visser, U. & DeAngelis, D. L. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, *198*(1–2), 115–126

Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J. & Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling*, *221*(23), 2760–2768

Grimm, V., Polhill, G. & Touza, J. (2017). Documenting social simulation models: The ODD protocol as a standard. In B. Edmonds & R. Meyer (Eds.), *Simulating Social Complexity (Understanding Complex Systems)*. Berlin Heidelberg: Springer

Grune-Yanoff, T. & Weirich, P. (2010). The philosophy and epistemology of simulation: A review. *Simulation and Gaming*, *41*(1), 20–50

Hamnett, C. (2001). Social segregation and social polarization. In R. Paddison (Ed.), *Handbook of Urban Studies*. London: Sage

Hegselmann, R. (2017). Thomas C. Schelling and James M Sakoda: The intellectual, technical, and social history of a model. *Journal of Artificial Societies and Social Simulation*, *20*(3), 15

Hodgson, G. M. (2000). The concept of emergence in social science: Its history and importance. *Emergence*, *2*(4), 65–77

Humphreys, P. (2009). The philosophical novelty of computer simulation methods. *Synthese*, *169*, 615–626

Jackson, W. A. (1999). Dualism, duality and the complexity of economic institutions. *International Journal of Social Economics*, *26*(4), 545–558

Janssen, M. C. W. (1993). *Microfoundations: A Critical Inquiry*. London: Routledge

King, A. (2000). Thinking with Bourdieu against Bourdieu: A 'Practical' critique of the habitus. *Sociological Theory*, *18*(3), 417–433

Kitcher, P. (1990). The division of cognitive labor. *The Journal of Philosophy*, *87*(1), 5–22

Kuhn, T. S. (1962). *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press

Lenhard, J. (2017). Thought experiments and simulation experiments. In M. Stuart, Y. Fehige & J. R. Brown (Eds.), *Exploring Hypothetical Worlds*, (pp. 484–497). London: Routledge Taylor & Francis Group

Leombruni, R. & Richiardi, M. G. (2005). Why are economists sceptical about agent-based simulations? *Physica A*, *355*(1), 103–109

Lorscheid, I., Heine, B. O. & Meyer, M. (2012). Opening the 'black box' of simulations: Increased transparency and effective communication through the systematic design of experiments. *Computational and Mathematical Organization Theory*, *18*(1), 22–62

Louis, M. R. (1980). Surprise and sense making: What newcomers experience in entering unfamiliar organizational settings. *Administrative Science Quarterly*, *25*(2), 226–251

Macal, C. M. & North, M. J. (2006). Introduction to modeling and simulation. MCS LANS Informal Seminar, Argonne National Library. Available at: `https://www.mcs.anl.gov/~leyffer/listn/slides-06/MacalNorth.pdf`. Accessed on 26 June 2014

Macy, M. W. & Flache, A. (2011). Social dynamics from the bottom up: Agent-based models of social interaction. In P. Hedstrom & P. Bearman (Eds.), *The Oxford Handbook of Analytical Sociology*, (pp. 245–268). Oxford: Oxford University Press

Manzo, G. (2014). Potentialities and limitations of agent-based simulations: An introduction. *Revue Française de Sociologie*, *55*(4), 653–688

Martin, J. L. & Lee, M. (2015). Social structure. In J. D. Wright (Ed.), *International Encyclopedia of the Social & Behavioral Sciences*, (pp. 713–718). Amsterdam: Elsevier

Marx, K. (1852). *The Eighteenth Brumaire of Louis Bonaparte*. New York, NY: Die Revolution

Merton, R. K. (1938). Social structure and anomie. *American Sociological Review*, *3*(5), 672–682

Meyer, R. (2015). Event-driven multi-agent simulation. In F. Grimaldo & E. Norling (Eds.), *Multi-Agent-Based Simulation XV. MABS 2014. Lecture Notes in Computer Science*. Berlin Heidelberg: Springer

Millington, J. D. A., O'Sullivan, D. & Perry, G. L. W. (2012). Model histories: Narrative explanation in generative simulation modelling. *Geoforum*, *43*(6), 1025–1034

Morgan, M. (2003). Experiments without material intervention. Model experiments, virtual experiments and virtually experiments. In H. Radder (Ed.), *The Philosophy of Scientific Experimentation*, (pp. 216–235). Pittsburgh, PA: University of Pittsburgh

Müller, B., Balbi, S., Buchmann, C. M., de Sousa, L., Dressler, G., Groeneveld, J., Klassert, C. J., Bao Le, Q., Millington, J. D. A., Nolzen, H., Parker, D. C., Polhill, J. G., Schlüter, M., Schulze, J., Schwarz, N., Sun, Z., Taillandier, P. & Weise, H. (2014). Standardised and transparent model descriptions for agent-based models: Current status and prospects. *Environmental Modelling & Software*, *55*, 156–163

Müller, B., Bohn, F., Dressler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. & Schwarz, N. (2013). Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software*, *48*, 37–48

Napoletano, M. (2018). A short walk on the wild side: Agent-based models and their implications for macroeconomic analysis. *Revue de l'OFCE*, *3*, 257–281

Newman, J. (2015). Epistemic opacity, confirmation holism and technical debt: Computer simulation in the light of empirical software engineering. In F. Gadducci & M. Tavosanis (Eds.), *History and Philosophy of Computing – Third International Conference*, (pp. 256–272). Berlin Heidelberg: Springer

O'Sullivan, D. & Perry, G. L. W. (2013). *Spatial Simulation: Exploring Pattern and Process*. Hoboken, NJ: John Wiley & Sons

Page, S. E. (2002). Aggregation in agent-based models of economies. *The Knowledge Engineering Review*, *27*(2), 151–162

Parsons, T. (1937). *The Structure of Social Action: A study in Social Theory with Special Reference to a Group of Recent European Writers*. Cambridge: The Free Press

Peuquet, D. J. (2005). Time in GIS and geographical databases. In P. Longley, M. F. Goodchild, D. J. Maguire & D. W. Rhind (Eds.), *Geographical Information Systems*. Hoboken, NJ: John Wiley & Sons

Polanyi, M. (1962). The republic of science: Its political and economic theory. *Minerva*, *38*(1), 1–32

Polhill, G. (2010). ODD updated. *Journal of Artificial Societies and Social Simulation*, *13*(4), 9

Polhill, J. G. (2015). Extracting OWL ontologies from agent-based models: A Netlogo extension. *Journal of Artificial Societies and Social Simulation*, *18*(2), 15

Polhill, J. G. & Gotts, N. M. (2009). Ontologies for transparent integrated human-natural system modelling. *Landscape Ecology*, *24*, 1255

Polhill, J. G., Parker, D., Brown, D. & Grimm, V. (2008). Using the ODD protocol for describing three agent-based social simulation models of land-use change. *Journal of Artificial Societies and Social Simulation*, *11*(2), 3

Porpora, D. V. (1989). Four concepts of social structure. *Journal for the Theory of Social Behaviour*, *19*(2), 195–211

Radcliffe-Brown, A. R. (1940). On social structure. *The Journal of the Royal Anthropological Institute of Great Britain and Ireland*, *70*(1), 1–12

Railsback, S. F. (2001). Concepts from complex adaptive systems as a framework for individual-based modelling. *Ecological Modelling*, *139*(1), 47–62

Raub, W., Buskens, V. & van Assen, M. A. L. M. (2011). Micro-macro links and microfoundations in sociology. *Journal of Mathematical Sociology*, *35*(1–3), 1–25

Relph, E. (1976). *Place and Placelessness*. London: Pion Limited

Roos, M. W. M. (2016). Modeling radical uncertainty and anticipating uncertain change with models. *Forum for Social Economics*, *50*(2), 1–19

Saam, N. J. (2017). Understanding social science simulations: Distinguishing two categories of simulations. In M. Resch, A. Kaminski & P. Gehring (Eds.), *The Science and Art of Simulation*, (pp. 67–84). Berlin Heidelberg: Spinger

Schlüter, M., Baeza-Castro, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M., McAllister, R. R. J., Müller, B., Orach, K., Schwarz, N. & Wijermans, N. (2017). A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics*, *131*, 21–35

Seth, A. K. (2002). Agent-based modelling and the environmental complexity thesis. In J. Hallam, D. Floreano, B. Hallam, G. Hayes & J.-A. Meyer (Eds.), *From Animals to Animats 7: Proceedings of the Seventh International Conference on the Simulation of Adaptive Behavior*, (pp. 13–24). Cambridge, MA: MIT Press

Sohl, T. L. & Claggett, P. R. (2013). Clarity versus complexity: Land-use modeling as a practical tool for decision-makers. *Journal of Environmental Management*, *129*(15), 235–243

Starbuck, W. H. & Milliken, F. J. (1988). Executives' perceptual filters: What they notice and how they make sense. In D. Hambrick (Ed.), *The Executive Effect: Concepts and Methods for Studying Top Managers*, (pp. 35–65). Greenwich, CT: JAI Press

Tesfatsion, L. (2006). Agent-based computational economics: A constructive approach to economic theory. In L. Tesfatsion & K. L. Judd (Eds.), *Handbook of Computational Economics*, (pp. 831–880). Amsterdam: North-Holland

Tuan, Y. F. (1977). *Space and Place: The Perspective of Experience*. Minneapolis, MN: The University of Minnesota Press

Waterman Jr., R. H. (1990). *Adhocracy: The Power to Change*. Memphis, TN: Whittle Direct Books

Watson, G. (1975). Free agency. *The Journal of Philosophy*, *72*(8), 205–220

Weber, M. (1922). *The Nature of Social Action*. Cambridge: Cambridge University Press

Weisberg, M. (2007). Who is a modeler? *The British Journal for the Philosophy of Science*, *58*(2), 207–233

Weisberg, M. (2013). *Simulation and Similarity: Using Models to Understand the World*. Oxford: Oxford University Press

Wendt, A. E. (1987). The agent-structure problem in international relations theory. *International Organisation*, *41*(3), 336–370

Wippler, R. & Lindenberg, S. (1987). Collective phenomena and rational choice. In J. C. Alexander, B. Giesen, R. Münch & N. J. Smelser (Eds.), *The Micro-Macro Link*, (pp. 135–152). Berkeley, CA: University of California Press