Agent-based complex systems and agent-based modeling

(Working paper document)

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1. Online data collection

In order to characterize temporal trends and disciplinary composition of agent-based modeling (ABM) papers, we performed an online bibliographic search. The dataset supporting this analysis was built upon Scopus records, which extensively cover the scientific literature. Queries were sent on 17 February 2020 to retrieve the entire ABM corpus by selecting all papers from 1980 to 17 February 2020, including "agent-based model*" and "individual based model*", respectively, in title, abstract, or keywords. For the purpose of comparison, we also searched all papers for "differential equations" for the same time span. Scopus supports native lemmatization, allowing for consideration of inflected forms of words. We enhanced this feature by using a basic regular expression (the wildcard in the search pattern), which ensured the inclusion of all derived terms (e.g., "individual-based modelling", "agent-based model").

The Diderot package [26] was then used to merge the datasets, remove duplicates, and produce annual publication and author counts based on 32,145 unique publication records. Data about sciences in which ABM is used are based on the classification of publications in research domains as provided by Scopus. Scopus research domains were further grouped into the main scientific branches, namely social sciences, life sciences, physical sciences, medical sciences, engineering, and formal sciences. The term "formal science" represents disciplines concerned with formal systems, such as logic, mathematics, statistics, theoretical computer science, information theory, game theory, systems theory, decision theory, and portions of linguistics (http://en.wikipedia.org/wiki/Formal_science; last accessed February 12, 2021).

2. Guidelines for modelers and reviewers

A common issue with agent-based complex systems (ACS) science, including ABMs, is that their complexity makes them difficult to document and communicate to others. Adopting a standard and widely used set of guidelines for developing, presenting, and evaluating ABMs will help the ABM field adhere to standards for scientific rigor and improve the scientific review and publication process. For modelers, we recommend practicing the following: 1) use a protocol to guide model development and description; 2) engage with and share the model validation process; and 3) take steps to increase model transparency and reproducibility.

1.1 Use a protocol to guide model development and description

For modelers, an important guideline is to use a standard protocol to develop and describe an ABM. By having a standard protocol, ABMs become more reproducible and rigorous. Employing a protocol forces the model developer to systematically confront the model's purpose, its features, and how these are justified and communicated. While following a protocol, the developer is forced to grapple with challenging or ambiguous concepts and make sure they add value to the model and can be clearly explained. Having an organized protocol subsequently helps reviewers of scientific ABM articles evaluate the rigor, replicability, and relevance of ABMs. Thus, by engaging with a set of standard ABM development and modeling guidelines, ABM developers simultaneously improve model quality and aid reviewers.

We recommend using an established protocol with modifications as needed to develop and describe an ABM, especially within a scientific publication. Many people in the ABM field have adopted variations of the ODD protocol [1] (see An et al. [2] for modifications for coupled natural and human systems). The ODD is a prescriptive protocol, dividing a model's description into categories (Overview, Design concepts, and Details). While the ODD categorization scheme cannot fit the needs of developing and describing every ABM [3], the protocol has proven flexible and useful for characterizing and presenting a wide diversity of ABMs [1]. Müller et al. provided detailed discussion on the standardization and transparency of ABMs based on three types of model description, including natural language description (represented by ODD), graphics, and formal language descriptions (e.g., source code and ontologies) [3].

In addition to using a protocol to produce a detailed model description, developers should consider using techniques like pattern-oriented modeling (POM) [4] and TRAnsparent and Comprehensive model Evaluation (TRACE) [5]. TRACE protocol, generically applicable to other models, warrants the appropriate design, implementation, testing, and use of ABMs. Of course, other modeling evaluation guidelines exist. For example, a policy-oriented evaluation framework was proposed in the book by Wallace et al. [6]. It is important that modelers follow these guidelines to rigorously evaluate their ABMs. Compiling TRACE documentations is facilitated by keeping "modelling notebooks", which correspond to "lab notebooks/journals", and using TRACE terminology to tag the notebook entries [7].

The above techniques help ensure ABMs are thoughtfully designed, considered, implemented, and evaluated from initial stages of model development. POM is a set of strategies that assist a developer in reducing complexity in an ABM (e.g., by exploring which variables to include or remove and by outlining strategies for testing hypotheses in an ABM). TRACE is a tool for comprehensively documenting the entire process of designing an ABM, from initial brainstorming about model concepts to its implementation in a programming language to analyzing and communicating results. ODD can be used as a complement to both POM and TRACE (e.g., one part of the TRACE technique is writing a model description, which the ODD protocol can be used for).

1.2 Engage with model validation and share the process

Model validation is a notoriously difficult issue [8] with no single standard or method within the ABM community [9]. Validation is especially critical for ABMs that are intended to be used for decision-making purposes [10]. To improve the applicability and acceptance of ABM as a scientific method, it is important that researchers consider how they will validate their ABM as part of the model development process. The model developer should consider the following issues: are there empirical data that can be used or for specific components or submodels? Are there multiple datasets or years of data such that a portion of the data can be reserved for validation purposes? If quantitative data are unavailable, can qualitative data be accessed and used to validate model patterns? If the ABM is used to inform a specific decision-making process, can the researcher use creative validation methods such as games [11]? See Windrum et al.'s work for more discussion of validation methods for ABMs [12]. In addition to actually conducting validation, ABM developers should be explicit and transparent about the methods they have used, especially in scientific publications.

1.3 Take steps to increase model reproducibility

Another common issue identified within the ABM community, including the ABM '17 symposium participants, is that ABMs are often opaque and difficult to reproduce. One of the most important ways, and perhaps a golden standard, to improve the reproducibility of an ABM is to make well-commented model code readily available. There are a variety of platforms or public repositories to enable this process, including Github (https://github.com/) and the model library of CoMSES (https://www.comses.net/). The documentation and sharing of the code of ABMs has been highly recommended by academic journals such as *Environmental Modeling and Software*, *Journal of Artificial Societies and Social Simulation*, *Ecological Modeling*, and *International Journal of Geographical Information Science*. If the model developer cannot share their code, they should both justify their reasoning and be particularly thorough in providing pseudo code and details that would help others reproduce their model. Even if parts of a dataset cannot be provided (e.g., due to human subjects and/or institutional review board constraints), modelers should make every effort to provide simulated datasets or the portions of code that are permissible. For more information on ABM code sharing, please refer to Tang et al [13] in which code transparency and reusability of ABMs are discussed from a cyberinfrastructure perspective.

Reviewers of ABMs can also follow a set of guidelines to ensure they are effectively and consistently evaluating the most important conceptual and methodological issues tied to any given ABM. We recommend that reviewers ask themselves the following essential questions about any ABM:

1) Does the research lend itself to using an ABM? Why or why not?
2) Could someone outside the ABM field (e.g., someone unfamiliar with ABMs) describe the model's purpose and results? Do the authors include conceptual diagrams to help with this where appropriate?
3) Is the model clearly described with a standard protocol like the ODD?
4) Is the model code made available? Does it run? Is it commented to aid with reproducibility?
5) Is model validation conducted and discussed? This is especially important to consider if the authors make any claims about using the model for applied or decision-making purposes.
6) Do the authors' broader claims about model implications seem reasonable given their results?

A series of guidelines have been developed for the presentation and evaluation of agent-based modeling to achieve scientific rigor and for acceptance for publication. For more details and publications related to these guidelines, see this site: Presentation and Evaluation Guidelines for Agent-Based Models (http://www2.econ.iastate.edu/tesfatsi/amodguide.htm).

3. *Guidelines for ACS/ABM novices*

Anyone interested in modeling ACS or learning ABM could focus on the representation of agents, environments, and interactions at the initial stage. The representational power of ABMs allows us to explore and understand complex dynamic phenomena that often emerge from bottom-up processes.

Entering the world of ABM development and evaluation can be an intimidating endeavor. The ABM novice may face many potential challenges, from developing methodological skills (e.g., programming) to knowing the best practices and understanding what types of questions are most suitable for being addressed with ABMs.

We first provide a list of introductory books. In the book by Epstein and Axtell [14], the authors used Sugarscape as a generic ABM in which the concept of sugar was introduced to represent resources in the environment that agents interact with. The Sugarscape model allows for the simulation of alternative complex phenomena in our societies, which emerge from bottom-up processes. These phenomena include, but are not limited to, social networking, migration, disease spread, culture, and markets. Sugarscape has been implemented in a series of ABM software platforms.

The book by Railsback and Grimm introduced the design, development, and use of ABM from a practical perspective [15]. This book guides readers to learn ABM by combining modeling cycle and NetLogo implementations. The ODD protocol was introduced at the beginning of the book, which provides a standard template for the documentation and sharing of ABMs. Fundamental topics related to modeling design are covered, including emergence, sensing, interaction, and stochasticity. This book also covers pattern-oriented modeling and model evaluation (including sensitivity analysis, uncertainty analysis, and robustness analysis). The use of Netlogo in this book makes the learning of ABMs easier (and perhaps fun).

To establish good modeling practices from the beginning, we recommend that new agent-based modelers build (or sharpen) a foundational understanding of what models are and engage with ABM-specific guidelines. We recommend:

1) Develop or refresh an understanding of what a model is, explore the theoretical foundations of agent-based modeling, and critically evaluate the types of questions that are suited to being addressed with an ABM.
2) It is essential to communicate the model as clearly and precisely as possible, which represents best practices for modelers. Whenever possible adhere to the available protocols for model description [1,16,17]. If the word limit does not allow inclusion of the complete protocol in a publication, it can always be provided as Supplementary Information and a short model description can be given in the main text. The use of such protocols is advantageous for both modelers and reviewers. For modelers the use of ODD will ensure that no important details were forgotten when describing the model and for the reviewer such ODD use will speed up the review process by allowing the reviewer to quickly examine specific areas where they have further questions [5].
3) Modelers should take care to note all their decisions and actions made throughout the modeling cycle, by keeping notebooks and documenting every important step (from the formulation of the conceptual model, to the choices and tests made during model implementation, verification, and validation [6,8,19]). Such notebooks are useful not only for a book-keeping of what has been done so far but are also of great help later when describing the model and may save time both for the modeler and for the peers who would like to re-implement the model later on. Especially for novices it is important to realize that a large amount of time within a modeling project is spent on model testing and analysis. Therefore, it is essential to not spend the majority of time on implementation but rather plan carefully to have enough time to properly verify and validate the

model. Additionally, the model's robustness should be tested (i.e., finding out under what conditions the observed behavior is changing [19]). Consider going beyond developing a protocol and maintaining a lab notebook as you develop your model using a process like TRACE[6].

4) Practice implementing and understanding ABM outcomes with established platforms such as NetLogo (see Table S2). There are several textbooks that incorporate plentiful examples and are accessible to beginners. For example, these four books use the opensource platform NetLogo: 1) An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo[21], 2) Agent-Based and Individual-Based Modeling: A Practical Introduction[16], 3) Spatial simulation: exploring pattern and process[22], and 4) Agent-based models of geographical systems [22].
5) Modelers should make their source code publicly available whenever possible. This way the model code will be scrutinized by peers, which may result in spotting and correcting unwanted bugs. This will facilitate establishing a culture of transparency and build trust in agent-based models. Moreover, sharing the code will promote its reuse in other projects, advancing the field of agent-based modeling as a whole.

4. *Toolkits and software packages*

Below we have compiled common toolkits and packages that modelers of ACS, especially novices, can rely on. However, it is worth noting that this is a subset of available toolkits and packages. For a more comprehensive list, see Abar et al. [23].

Table S2: A selection of open-source ABM toolkits for creating geographically explicit models. The table is adapted and extended from Parker et al. and Castle and Crooks [24,25].

	Swarm	**MASON**	**Repast**	**NetLogo**	**GAMA**
Developers	Santa Fe Institute/SWARM Development Group, USA	Evolutionary Computation Laboratory and Center for Social Complexity, George Mason University, USA	University of Chicago, Department of Social Science Research Computing and Argonne National Laboratory, USA	Centre for Connected Learning and Computer-Based Modelling, Northwestern University, USA	UMMISCO, France
Date of inception	1996	2003	2000	1999	2007
Website	http://www.swarm.org/	http://cs.gmu.edu/~eclab/projects/mason	https://repast.github.io/	https://ccl.northwestern.edu/netlogo/	http://gama-platform.org/

Implementation language(s)	Objective-C/Java	Java	Java, Microsoft.Net Python, Groovy, ReLogo	NetLogo programming language	GAMA Modeling Language
Required programming experience	Strong	Strong	Medium to Strong	Little	Basic to Medium
Integrated GIS Functionality	Yes (e.g. Kenge GIS library for Raster data; Box, 2001)	Yes	Yes	Yes	Yes
Integrated charting/ graphing/ statistics	Yes (e.g. R and S-plus statistical packages)	Yes (e.g. wrappers for JFreeChart)	Yes	Yes	Yes
Availability of Demo. models	Yes	Yes	Yes	Yes	Yes
Tutorials / how-to documentation	http://www.swarm.org/wiki/Swarm_main_page	http://cs.gmu.edu/~eclab/projects/mason/docs/ Also Luke, 2015	https://repast.github.io/docs.html	https://ccl.northwestern.edu/netlogo/resources.shtml also Wilensky and Rand, 2015	http://gama-platform.org/tutorials
Additional Information	Minar *et al.*, 1996	D-MASON: www.dmason.org/ GeoMASON: http://cs.gmu.edu/~eclab/projects/mason/extensions/geomason/	Useful weblog: http://crimesim.blogspot.com/ Agent Analyst: http://resources.arcgis.com/en/help/agent-analyst/	NetLogo-R Extension: http://r-ext.sourceforge.net/ Selection of GIS examples: http://www.gisagents.org/search/label/NetLogo	GAMA GitHub page https://github.com/gama-platform

Note: Modified from the paper by [27].

For all the platforms identified in Table S2, we identify their strengths and weaknesses (Table S3). In addition, we add Ascape for its relative popularity.

Table S3. Strengths and weaknesses of major existing ABM platforms

Name	Strengths	Weaknesses	Note

Swarm	Open-source	No update after 2011; Based on Objective C Limited developer tools; unclear error messages	Version 2.4.1
Mason	Supports multiple programming languages including Java, C#; speed and execution prioritized Open source (Java-based)	Less extensive features; less mature and documented; not updated after 2015	Version 19
Repast	Timely updates (last update: 2017); Flexibility for customized modeling based on Java; Supports high-performance computing (via C++); Open source (Java-based); Integration with GIS capabilities	Need of medium- or advanced level of programming skills	Latest version: 2.5
Netlogo	Extensive documentation; open source, existing example library; arguably the most accessible, especially for those with limited programming experience	Not suitable for large systems (100 thousand of agents, millions of spatial units)	6.2
GAMA	High-level and intuitive language suitable for beginners; Open source; Support provided through an active mailing list (see https://gama-platform.github.io/wiki/Home)	Speed and execution is slower than some platforms	Version 1.8
Ascape	Open source (Java-based; http://ascape.sourceforge.net/)	Last update: 2011	Version 5.6.1
StarLogo	Low barrier to entry Designed for use by K-12 educators Well documented	Limited StarLogo language; Largely useful for educational purposes for K-12 students; Closed source	StarLogo Nova

For more information about ABM software platforms, we recommend the review article by Railsback et al. [27]. The authors compared five agent-based simulation platforms via the use of an ABM template, StupidModel. The comparison covers general aspects of simulation (including model structure, scheduling, and random number generation), programming experience, and execution speed. For a recent review on ABM software platforms, readers may check out the work by Kravari and Bassiliades [28] and by Abar et al. [24]. If readers are interested in learning how to write their own agent-based simulation platform, we refer to the paper by Tang [29].

Also, a series of online guides are available for beginners of ABM. One of them is the "On-Line

Guide for Newcomers to Agent-Based Modeling in the Social Sciences" by Robert Axelrod and Leigh Tesfatsion, including a detailed collection of readings and software packages for ABM novices (http://www2.econ.iastate.edu/tesfatsi/abmread.htm), for a variety of resources for beginners in specific topical areas of agent-based modeling, like economics, evolution, and methodological issues. While these suggestions have a focus on social science, they provide ABM newcomers comprehensive training on agent-based modeling. For more information on ABM in terms of books, courses, and tutorials, please refer to the Educational Materials section on CoMSES (https://www.comses.net/resources/education/).

5. ACS education and communication

Education is an essential element in ACS science. As agent-based modeling courses are increasingly taught in different universities, ABM scholars may coordinate efforts to develop (and share if possible) ABM curricula at various educational levels (e.g., beginning with the undergraduate level). This effort will facilitate sharing teaching resources and materials and ensure the next generation of agent-based modelers will have a similar "core" training. For example, ABM development could follow the ODD protocols for documentation [1,16] and the modeler could evaluate ABM performance following the four aspects summarized by Tesfatsion [30]. These can partly address the transparency and reusability of ABM at least for the next generation of ABM modelers in different subjects. Such core training may provide the next generation of ABM developers with a better opportunity to understand and reuse each other's models.

This can be a step-by-step process. We suggest the first step is to share syllabi and recommend common textbooks to synchronize teaching plans among universities. The second step is to ensure each ABM course covers the essential and common knowledge in model development by co-developing course materials like lecture presentations and homework assignments. The third step is to allow students to have hands-on experiences in ABM building by, for example, creating a "joint" project between different universities where students from each school can represent one or more agents on a web-based platform. For annotated pointers to ABM-related information, see the following site: ACE/ABM Course and Program Information at http://www2.econ.iastate.edu/tesfatsi/teachsyl.htm. At the same time, academic researchers and practitioners should begin communicating with industry professionals, leveraging engineers in computer games.

Communicating models within and across disciplines is often difficult [31]. Although ODD (+D) is helpful for the end product [32], an easier communication strategy is often warranted throughout the modeling process, and to show how the model responds to different assumptions and changes in parameters. Notebooks of different styles (Jupyter, Rmarkdown, etc.) allow for communicating model progress throughout the model development process [7]. A solution to communicate the model "in action" could be to use the interactive notebook Jupyter (https://jupyter.org/) as a platform for collaboration and communication between developers of different backgrounds. It serves as a dynamically changing notebook that integrates text, code, data, and figures related to a project. Throughout a project, Jupyter may be used to serve as a platform for sharing and creating a joint understanding of the project in its different development phases. Besides collaborations between scholars and other actors, it is highly suitable for teaching and learning because of its abilities to run code through the Jupyter interface, changing input data and parameters, re-creating figures, and adding blocks of code or text.

We have engaged subfield experts to identify a set of impending challenges in several topical subareas so as to unify the relatively fragmented ABM endeavors through communication, coordination, and collaboration (http://complexities.org/ABM17/). This will help prioritize specific resources and activities in relation to ABM advances, leading to coordinated efforts and initiatives to advance the science and technology behind ABMs. There exist a large number of ABM applications worldwide, but many fall short of convincing others of the usefulness (e.g., offering unique insights) of ABM. Though we do not intend to find a one-size-fits-all solution in one paper, it is time to engage people power and resources, with higher priority, to address the challenges we have identified, and this paper is a precursor in this regard. We call to assemble greater efforts and resources, including engaging the broader ABM community (developers/software engineers, users, domain knowledge experts), to not only ABM development and application, but also to education.

In terms of collaboration, we need coordinated efforts, leveraging existing resources (e.g., http://chans-net.org/, https://www.comses.net/), reducing redundant investment of time, efforts, and funds. In the technical and theoretical aspects, efforts should be devoted to lower the threshold of ABM. ABM still has a sharp learning curve, which requires substantial skills and knowledge in computer programming and mathematics. If ABM “Lego” or “Mr. Potatohead” pieces can be crafted and made readily available (as open source or commercial products), more people, including those with less programming or mathematics background, can “develop” and use ABM.

From a documentary perspective, we need to set up standards that are commonly accepted by ABM developers and users. As the Overview, Design concepts, and Details (ODD) protocol is increasingly adopted, other protocols, languages, and/or morals may need to be established about sharing modules and code, documenting models, and dealing with related authorship and data confidentiality issues (e.g., sensitive human subjects data protected by institutional review boards). From a communication aspect, we need to facilitate relatively easier, more frequent communication between domain knowledge (e.g., for human decision making), experts, and ABM developers. Ideally, these experts themselves understand ABM (if the threshold mentioned above is lowered enough) and its pros and cons. Achieving these aims hinges upon the previous recommendation about education.

One of the key and arguably most difficult tasks of modeling is to decide the level of details and complexity that are necessary to depict the system and answer the question(s) of interest [33]. Therefore, novices—experienced modelers also at the beginning of a new modeling project—must make sure to search for the models that were developed previously for the same or similar purpose/system. If such models are available then re-implementing the existing model and whenever necessary extending or modifying it is often a better solution rather than developing a model anew [34].

6. Review of COVID-19 agent-based models

Agent-based models are well-suited to investigate epidemics because they are able to represent dynamic interaction and contact networks and the effects of behavior and environmental heterogeneity. They have been successfully used to model human [35] and wildlife [36] epidemics. Accordingly, ABMs have been quickly developed to cope with COVID-19. Below we search the papers using ABM to deal with COVID-19 and look into their strengths and weaknesses.

In Web of Science, we searched "COVID-19" AND "Agent-based model" for “topics” and found 15 peer-reviewed publications that vary in model objectives, geographical location, spatial extents, and temporal ranges. Most studies focused on simulating spread of the disease under different non-pharmaceutical interventions within certain spatial extents, whereas others modeled the potential socioeconomic impacts induced by the pandemic as well as the social-distancing policies. Most models in these studies were conceptual, either totally dependent on social networks or situated in hypothetical facilities. A few cases incorporated extensive real-world demographic and socioeconomic records, being spatial-explicit and connected to detailed geographical information.

Worthy of mention are a subset of representative papers thus found. ABM has been used to explore how various combinations of aisle social distance, luggage volume, and number of boarding groups may reduce COVID-19 risks during any airplane boarding process [37]. In an agent-based model of disease transmission among connected families, workplaces, and social groups, various mitigation strategies (e.g., targeted quarantine measures) are tested [38]. To help residential colleges and universities handle unique challenges during the COVID-19 pandemic, an agent-based model is developed to determine whether in-person instruction could safely continue and evaluate the necessity of various interventions [39]. In terms of parameterizing ABM, data mining approaches can be leveraged to analyze a trove of potential qualitative datasets collected from publicly available social media postings about COVID-19 [40]. We summarize all these ABMs as follows (Table S1).

Table S1a Summary of ABMs that handle COVID-19

Author(s)	Manuscript Title	Journal	Purpose of ABM
Abdollahi et al.	Simulating the effect of school closure during COVID-19 outbreaks in Ontario, Canada	BMC Medicine	The effect of school closure on COVID infection rate and need for critical care
Aleta et al.	Modelling the impact of testing, contact tracing, and household quarantine on second waves of COVID-19	Nature Human Behavior	Quantitatively analyze the evolution of the epidemic and the effectiveness of social-distancing interventions
Araya 2021	Modeling the spread of COVID-19 on construction workers: An agent-based approach	Safety Science	Spread of COVID-19 among construction workers
Chang et al.	Modelling transmission and control of the COVID-19 pandemic in Australia	Nature Communications	Evaluate and compare several mitigation and suppression measures

Cotfas et al.	Evaluating Classical Airplane Boarding Methods Considering COVID-19 Flying Restrictions	Symmetry	Airplane boarding methods, jet bridges and one-door boarding
Cremonini & Maghool	The Unknown of the Pandemic: An Agent-Based Model of Final Phase Risks	JASSS	Evaluate the risk associated with lifting social restrictions
Cuevas	An agent-based model to evaluate the COVID-19 transmission risks in facilities	Computers in Biology and Medicine	Evaluate transmission risks in facilities
Eilersen & Sneppen	Cost–benefit of limited isolation and testing in COVID-19 mitigation	Scientific Reports	Cost-benefit of limited lockdown and testing
Gressman & Peck	Simulating COVID-19 in a university environment	Mathematical Biosciences	Whether in-person instruction could safely continue during the pandemic; necessity of various interventions
Hernandez-Meija & Hernandez-Bargas	When is SARS-CoV-2 in your shopping list?	Mathematical Biosciences	COVID-19 spread in a small size supermarket
Hoertel et al.	A stochastic agent-based model of the SARS-CoV-2 epidemic in France	Nature Medicine	Potential impact of post-lockdown measures on cumulative disease incidence, mortality, and ICU-bed occupancy
Inoue & Todo	The propagation of economic impacts through supply chains: The case of a megacity lockdown to prevent the spread of COVID19	Plos One	Quantify the economic effect of a possible lockdown of Tokyo
Milne et al.	Evaluation of Boarding Methods Adapted for Social Distancing when using Apron Buses	IEEE Access	Airplane boarding methods, when using apron buses

Nishi et al.	Network interventions for managing the COVID-19 pandemic and sustaining economy	PNAS	Investigate two network intervention strategies for mitigation the spread while maintaining economic activities
Zhang et al.	Impact of intervention methods on COVID-19 transmission in Shenzhen	Building and Environment	Efficiency of various intervention strategies to prevent COVID-19 infection

Table S1b Summary of ABMs that handles COVID-19 (Continued)

Author(s)	**Agents**	**Space**	**Time range/ resolution**	**Spatial extent/resolution**
Abdollahi et al.	Person (10000 in total, five age groups, stratified according to demographics)	Social network based, not spatial explicit	Feb 14, 2020 ~ Oct 10, 2020 / Daily	Hypothetical / N/A
Aleta et al.	Person (64000 adults and 21000 children)	Boston metropolitan area	Feb 16 ~ Dec 20 / Daily	Boston metropolitan area / Census block group
Araya 2021	Construction workers (100 in total)	A hypothetical construction site	three working months (1440h) / Hourly	Hypothetical / N/A
Chang et al.	Person (one for each people in Australia, 24 million in total)	Australia	Feb 3 ~ Aug 21 / 12 hours ("day" and "night")	The whole Australia / Census collection districts (avg. 225) within 1422 statistical local areas
Cotfas et al.	Patch (aisles and seats) / Person (passengers)	A hypothetical plane	Whenever boarding was finished / Seconds	Airplane space / Patch size (in NetLogo): 0.4 m by 0.4 m
Cremonini & Maghool	Person (population size: 1000)	Network based, not spatial explicit	Time steps: 150	Hypothetical / N/A

Cuevas	Person (susceptible or infected)	Hypothetical space developed in NetLogo	Time steps: 500	Hypothetical / N/A
Eilersen & Sneppen	Person	Network based, not spatial explicit	300 days / 0.5 day	Hypothetical / N/A
Gressman & Peck	Person (22500 in total)	A hypothetical big university	100 days / Daily	A large university (hypothetical) / N/A
Hernandez-Meija & Hernandez-Bargas	Person	A hypothetical supermarket	N/A	Hypothetical (a supermarket, 30 m * 16 m) / N/A
Hoertel et al.	Person (500000 individuals)	France; network based, not spatial explicit	360 days / Daily	France / N/A
Inoue & Todo	Supply chain firms (966627 in total, number of links 3544343)	Network based, not spatial explicit	100 days / daily	Tokyo, Japan / N/A
Milne et al.	Person (22500 in total)	A hypothetical big university	100 days / Daily	A large university (hypothetical) / N/A
Nishi et al.	Person	A hypothetical supermarket	N/A	Hypothetical (a supermarket, 30 m * 16 m) / N/A
Zhang et al.	Person (500000 individuals)	France; network based, not spatial explicit	360 days / Daily	France / N/A
Plos One	Supply chain firms (966627 in total, # of links 3544343)	Network based, not spatial explicit	100 days / Daily	Tokyo, Japan / N/A

Table S1c Summary of ABMs that handles COVID-19 (Continued)

Author(s)	Strengths of the ABM	Weaknesses of the ABM

Abdollahi et al.	parameterized with demographics stratified by age and latest epidemiologic characteristics	1. Findings are based on early estimations of and may be subject to uncertainty. 2. The effect of other social distancing measures were not addressed.
Aleta et al.	explore with different strategies; agents representative of different census areas; can model individual transactions	1. Very large uncertainties around the transmission of the disease; 2. Estimates of age-specific severity are informed by data from China and other countries, and subject to change as more US data become available; 3. Do not include specific co-morbidities or pre-existing conditions of specific population; 4. Did not consider potential changes to virus transmissibility due to environmental factors.
Araya 2021	model behavior individually, analyze emergent behavior, and model different scenarios	1. Oversimply activities into classifications: low / medium high risk; 2. Lack of actual data from a real project to simulate construction workers' behaviors
Chang et al.	can trace fine-grained effect of heterogeneous intervention policies in diverse settings	1. Need finer-grained implementation of nature history of the disease; 2. Need to reduce the uncertainty around the transmissibility and infectivity in young people; 3. Can incorporate more recent Australian Bureau of Statistics data from 2020; 4. Account for hospitalizations and in-hospital transmissions; 5. Trace specific spatial pathways and patterns of epidemics
Cotfas et al.	provide the needed basis for imitating the details of a mechanism or a real process without involving too much statistical or mathematical modeling	N/A
Cremonini & Maghool	can address uncertainty by considering a range of possible values in a scenario-oriented approach	N/A
Cuevas	Model individuals with distinct characteristics and provide more realistic results	1. Does not implement the behavior of the complete disease, thus impossible to assess the way in which the risk decreases when recovered individuals are not able to

		transmit; 2. Rules are simple, thus complex interactions among agents are not modeled.
Eilersen & Sneppen	can address different infection parameters and case specific strategies	N/A
Gressman & Peck	uniquely well-suited to the situation because behavior in an academic environment is highly structured spatially and temporally, which can lead to consistent overestimations of disease incidence when other tools are used	1. Did not include seasonal effects in transmission patterns or the arrival of off-campus infections; 2. Have accounted for the fact that compliance with mask-wearing policies will likely be diminished in residential settings and social settings
Hernandez-Meija & Hernandez-Bargas	can model desired characteristics and behaviors of individuals and test different strategies	N/A
Hoertel et al.	N/A	1. Rely on existing knowledge and current assumptions; 2. Model was calibrated on diagnosis and morality rates available, may be underestimated due to asymptomatic undiagnosed patients
Inoue & Todo	can model the complex network characteristics of supply chains	1. Suppose firms cannot find any new suppliers; 2. Only considers the dynamics of production and ignores possible changes in prices and wages
Milne et al.	can easily incorporate variability of agent behavior	N/A
Nishi et al.	can model individual-level behavior and test different strategies under various scenarios	1. Only explored agent-based simulations with specific parameter spaces and with specific assumptions, 2. May not account for people's irrational in the real world.
Zhang et al.	can model micro-patterns such as personal decisions and preferences, spatial relationships of population and distributions of buildings, and the dynamic links between social and environmental processes	1. Assume COVID is only transmitted by close contact; 2. Ignored exposure in public transportation

In simulating COVID-19 related issues, ABMs can parameterize agents and attributes with empirical information, while also incorporating emergent characteristics throughout the simulations. ABMs can also address uncertainty by incorporating a range of possible values through a scenario-based approach. However, like any other modeling approaches, ABMs might inevitably over-simplify complex socioeconomic issues. ABMs rely on and calibrate with existing knowledge and current assumptions, which may be falsified as more information emerges.

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