Modeling the Impact of Social and Behavioral Factors on the Spread of Infectious Diseases in a Macro-Financial Agent-Based Model: A Methodological Proposal

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Abstract. The COVID-19 pandemic has profoundly affected multiple facets of society, including health and the economy. To mitigate its spread, governments worldwide have implemented containment policies, the success and effectiveness of which rely on population compliance. This paper proposes a novel methodological approach integrating psychology and health behavior research to formulate an evidence-based behavioral framework for compliance with pandemic-related interventions. This behavioral framework is integrated into the CliMaPan Lab, a macro-financial agent-based model that merges macroeconomic and financial dynamics, a climate module, and considers the endogenous emergence of infectious diseases. This integration enables the CliMaPan Lab to evaluate the effectiveness of containment policies and their economic impact while accounting for population behavioral responses. Overall, this innovative approach offers a more comprehensive understanding of the COVID-19 pandemic's impact and the effectiveness of containment policies. Recognizing the critical role that human behavior plays in shaping policies' economic and health-related impact, the proposed approach paves the way for better-informed policy decisions.

Keywords: Agent-based modeling · Behavioral rules · Methodology · Epidemics · Qualitative Evidence · Quantitative Evidence · Simulations

1 Introduction

Social and behavioral factors play a crucial role in the origin, transmission, and control of human diseases and significantly impact pandemics' development and consequences. However, these factors and their impact on community and individual responses are frequently studied separately from epidemiological patterns and biomedical strategies, even in disease modeling (Bedson et al., 2021).

The field of pandemic modeling exerts a substantial and increasing impact on critical issues relating to public health policy (Heesterbeek et al., 2015) and

the economic repercussions of pandemic crises (see,e.g., Safaei and Saliminezhad, 2022; Wu et al., 2023). The recent SARS-CoV-2 pandemic has prompted a rapid proliferation of literature investigating its epidemiology, immunization, and economic effects. Nevertheless, despite the evident need and possible advantages, advancement towards more integrated disease modeling has been sluggish (Bedson et al., 2021). On the one hand, conventional compartmental models suffer from the limitation of not accounting for the local transmission dynamics that may depend on individuals' health characteristics and a realistic disease progression model. On the other hand, prevailing agent-based models inadequately incorporate the influence of social and behavioral factors.

This paper presents a methodological approach that utilizes psychology and health behavior research to develop a qualitative and quantitative evidence-based behavioral framework for adherence to COVID-19 interventions. The resulting behavioral rules are then incorporated into the *CliMaPan Lab*, an existing modeling framework that integrates macroeconomic and financial dynamics, a climate module, and accounts for the *endogenous* emergence of infectious diseases such as COVID-19. Integrating evidence-based behavioral rules in the macro-financial simulation allows for explicitly considering the role of human behavior in shaping both the economic and health-related impact of policies. In doing so, the presented methodology addresses two issues. Firstly, it responds to the inadequacy of existing agent-based models, which overlook compliance dynamics influenced by behavioral and social factors in epidemic spread and policy responses (Bedson et al., 2021; Squazzoni et al., 2020). Secondly, it contributes to the current efforts to develop agent-based economic models that are behaviorally rich and grounded in qualitative and quantitative evidence (Antosz et al., 2022), making them suitable for policy analysis and evaluation.

The remainder of the paper is organized as follows. Section 2 reviews the literature and puts the study in context. Section 3 presents the proposed methodological framework. Section 4 provides concluding remarks.

2 Background

Several methodologies exist to investigate strategies for controlling and preventing COVID-19 pandemic onset, spread, and resurgence (Gnanvi et al., 2021; Lorig et al., 2021), its impacts on economic and financial resilience and stability (Aday and Aday, 2020; Nicola et al., 2020).

Traditionally, the study of epidemic dynamics has relied on compartmental models that operate at the population level rather than the individual level (Ferguson et al., 2020). These models track changes in the different compartments without specifying the particular agents involved and typically represent health states pertinent to transmission, such as susceptible, exposed, infectious, and recovered. Compartmental models, although useful, may not fully account for the impact of diverse socio-economic behaviors, which can impede a comprehensive understanding of possible causal relationships associated with interactions among agents of distinct groups. The accurate simulation of disease transmission

necessitates the inclusion of (i) the nuances of local transmission dynamics that are contingent on individuals' health attributes, as well as (ii) a natural disease history model that pertains to the particular virus under investigation.

Agent-based models (ABMs) are particularly well-suited for investigating social phenomena, such as the transmission of diseases within a population of self-governing individuals with varying characteristics and behaviors (Arthur, 2013). ABMs allow for the inclusion of specific risk or age groups, individual disease progression, pre-existing medical conditions, adherence to interventions, and the characterization of personal contact networks such as households or workplaces and daily routines (Dignum et al., 2020; Squazzoni et al., 2020; Bedson et al., 2021). Consequently, ABMs can facilitate a deeper comprehension of a pandemic and identify suitable interventions to curtail the spread of the virus. Specifically, this approach enables the detailed modeling of the complex social dynamics arising from individuals' transmission, response, and compliance. In summary, employing an individual-level agent-based modeling approach offers a more complex and realistic depiction of the transmission of COVID-19 in contrast to alternative approaches that rely on aggregated or population-level data.

Existing models, however, incorporate the role played by social and behavioral factors only to a limited extent (see Lorig et al., 2021, for a review). Despite the extensive existing research on the determinants of compliance to COVID-19 pandemic measures in psychology and behavioral fields (see, e.g., Asnakew et al., 2020; Sheikh et al., 2020; Chambon et al., 2023; Georgieva et al., 2021), and models using socio-economic data to estimate behavioral heterogeneity in epidemiological diseases (see, e.g., Hunter et al., 2017), adherence to various interventions, referred to as non-pharmaceutical interventions (NPIs), is typically modeled as a parameter or probability in complex agent-based simulation studies of COVID-19 (see,e.g., Chang et al., 2020; Tatapudi et al., 2020; Kerr et al., 2021). However, *compliance* is contingent upon individual traits and contextual factors, which necessitates careful consideration; therefore, more sophisticated decision-making models are required (Squazzoni et al., 2020; Lorig et al., 2021).

3 Integrating evidence-based behavioral rules into agent-based simulations: our methodological proposal

3.1 Developing an evidence-based behavioral framework

The proposed methodology utilizes knowledge derived from a qualitative meta-analysis of research that investigates compliance with COVID-19 interventions to establish a behavioral framework grounded in empirical evidence. This behavioral framework is informed by qualitative and quantitative evidence synthesized in the meta-analysis, and its behavioral rules are integrated into the *CliMaPan* model. The methodology adopts a sequential process comprising five steps, visually depicted in Figure 1 and described in detail in the following.

Studies selection In October 2022, a search was conducted on Web of Science to gather relevant studies for the analysis. The primary aim was to identify survey

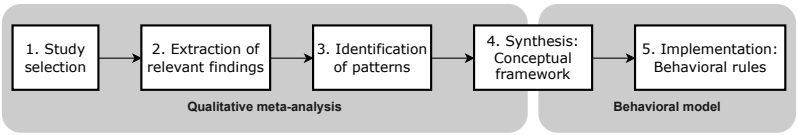

Fig. 1. The proposed behavioral framework is based on empirical evidence obtained from a qualitative meta-analysis. Source: Authors' elaboration.

articles investigating the determinants of compliance with preventive behaviors among the general population, focusing on threat perceptions and their interplay with other psychosocial factors. Specifically, the study targeted four groups of NPIs: social distancing, self-isolation, mask-wearing, and hygiene practices. The search term *"COVID-19 and (fear or risk) and (compliance or adherence or intention or ((preventive or protective or mitigation) and behavio*))"*, filtered by area of research, yielded 1,623 initial results, which were then sequentially screened by title, abstract, and full text. A final sample of 73 studies satisfied the inclusion criteria derived directly from the primary aim of the review, and were thus selected for the analysis. The selected studies reported survey data collected between January 2020 and April 2021 in 62 countries.

Extraction of relevant findings During the process of full-text assessment, evidence on predictors of COVID-19 preventive behaviors were collected from each study and compiled in a data extraction sheet. The extraction process focused on three types of findings: i) Direct and indirect predictors of compliance along with the corresponding effect sizes, ii) interrelations between those predictors, and iii) changes in the relative importance of predictors over time. Both quantitative and qualitative results were explicitly taken into account to ensure that the envisaged behavioral framework would be developed on the basis of a comprehensive and multi-layered data base.

Relevant predictors identified in the present sample encompassed demographic, psychological, and social characteristics, perceptions of the threat posed by the disease, the effectiveness of preventive behaviors in mitigating the risk, and self-reported motivations and barriers to adherence. These findings were recorded separately for each NPI if reported within the respective study.

Identification of patterns Upon assessing the data, recurring findings were identified and contradictory results evaluated. Subsequently, a collection of stylized facts was determined to be integrated into the behavioral framework. The patterns include, for instance, the disparate psychological costs associated with each preventive behavior, the complementary interplay of threat and efficacy perceptions, and the role of personality traits in shaping protection motivation.

Synthesis: developing the conceptual framework The intermediate stage linking the meta-analysis and model conceptualization entails formulating a conceptual framework that integrates all identified predictors and their interrelations into a

cohesive decision-making process at the individual agent level. While the overall structure of the decision process is the same for all NPIs, the exact configuration of each set of behavioral rules is individually adapted to the results of the meta-analysis, as illustrated in more detail in section 3.2.

Implementation: Formulating behavioral rules Ultimately, the conceptual framework shall be transformed into explicit behavioral rules that establish the degree of involvement of agents in the designated preventive behaviors. To guarantee seamless integration, the behavioral rules will be customized to suit the requirements of the CliMaPan model, such as agent design, network structures, and the degree of detail involved in simulating the pandemic.

3.2 The compliance decision model

To develop the behavioral framework, the most influential predictors identified in the literature review are embedded in an agent-level decision process. The additional patterns and interrelations derived from the meta-analysis are used to design the multilevel structure of the framework, resulting in a hierarchical process leading towards the final compliance decision.

Following this framework, an agent's behavioral decision at each time step arises from a cost-benefit assessment that weighs the motivating aspects and impediments associated with compliant behavior. This evaluation is further informed by two underlying processes, contributing indirectly to the final decision: First, it is influenced by the complementary interplay between an agent's threat and efficacy perceptions. Second, individual demographic and psychosocial traits play a moderating role in shaping the decision process, impacting the agent's cost-benefit assessment both directly and indirectly through their perceptions.

While this general framework applies to all NPIs under consideration, the specific components and functions vary for each preventive behavior.

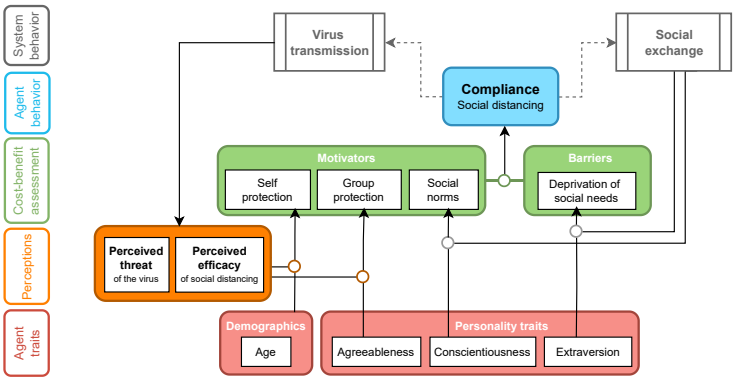

Fig. 2. Components of an agent's decision process leading towards the decision to comply with social distancing measures. Source: Authors' elaboration.

Figure 2 illustrates the decision process as applied to compliance with social distancing measures. The costs of adherence are conceptualized as frustration of social needs following the lack of interaction among agents in the model. In contrast, compliance is facilitated by agents' protection motivation, which is further divided into self-protection and group protection motivation. In addition, agents are influenced by the prevailing social norm, which emerges endogenously based on the observed level of compliance among other agents. At the perceptions level, an agent's perceived threat of the disease is shaped by the current number and severity of infections in the model. Higher threat perceptions, coupled with perceptions of high efficacy of social distancing measures, thus enhance the agent's self and group protection motivation.

Moreover, the meta-analysis identified a set of individual traits significantly related to compliance with social distancing measures, including respondents' age and certain personality traits. Acting as the main source of exogenous agent heterogeneity, they are implemented as moderators shaping the effects of specific higher-level determinants: Older age and agreeableness both enhance protection motivation, the former relating to self-protection and the latter to group protection. Extraversion, in contrast, increases the psychological cost associated with social distancing due to differences in social needs. Lastly, higher levels of conscientiousness contribute to engagement in preventive behaviors, as individuals are more persistent in adhering to prevailing social norms.

Accounting for the social nature of the pandemic, the framework thus embeds agents in a social and pandemic environment that directly influences agents' behavior while also being endogenously shaped by it.

3.3 The CliMaPan model

The proposed behavioral framework shall be integrated into a macro-financial agent-based model - the so-called CliMaPan model - that comprises three distinct modules. It serves as a conceptual framework for comprehending the interconnections and interactions between the system's components and its environment (Tesfatsion, 2006). The Epidemiological Module (EM) adopts a network approach where agents are represented as nodes connected to others through links. Individual agents are classified in different states, and the disease progression is modeled according to a SEIRD (Susceptible - Exposed - Infected - Recovered - Immunized/Dead) model. Infectious individuals are additionally categorized according to their symptoms, i.e., asymptomatic, pre-symptomatic, mild, severe, or critical. This EM module is incorporated into the Macro-Financial Agent-Based Model (ABM), which operates under the premise that macroeconomic and epidemiological dynamics are driven by the micro-level actions of individual agents, namely workers and capitalists in the household sector. The integrated ABM-EM model facilitates the study of the co-evolution of epidemiologic and economic dynamics, which is essential in comprehending the balance between implementing pandemic responses (i.e., the Non-Pharmaceutical Interventions) and their economic impact. The Climate Module incorporates the feedback loop between CO2 emissions and actual production, enabling the evaluation of the

impacts of epidemic diffusion and economic production on both the climate and the reciprocal influences between the economy and the climate.

3.4 Integrating the evidence-based behavioral rules in the CliMaPan Agent-based Model

Once incorporated into the CliMaPan model, the compliance behavioral framework extends the existing households' behavioral rules by refining their response to the simulated policy interventions. Equipped with these evidence-based rules, households' degree of adherence is determined by the dynamic evolution of the pandemic, as well as their heterogeneous characteristics and their social environment, i.e. the observed behavior of other agents. Thus, the integrated modeling framework accounts for interactions and feedback effects between behaviors on the micro and the macro level, subsequently shaping the development of each model component.

Ultimately, the agent-based modeling approach shall be used to analyze agents' behaviors, local interactions, and the progression of the disease while simultaneously examining the interplay between epidemic dynamics, the economy, and the climate. This integrated approach - enriched with evidence-based behavioral rules - functions as a policy laboratory for decision-makers, enabling investigation of the different climate, pandemic-related, macroeconomic, and financial stabilization strategies.

4 Concluding remarks

The compartmental modeling approach has contributed to our understanding of the threshold nature of epidemics and herd immunity. However, this approach is limited in capturing significant social and behavioral factors, such as the behavioral responses of individuals to policy measures and the influence of heterogeneous social contacts on diffusion patterns. Simulation models that estimate disease trajectories have proven useful for informing policy decisions to limit the spread of epidemics. However, they, too, fall short in their ability to account for the full complexity of social and behavioral dynamics that characterize societies during pandemics (Epstein, 2009; Currie et al., 2020).

The methodological approach proposed in this paper is based on explicit theoretical and empirical assumptions regarding individual behavior, social transmission mechanisms, and structural constraints. The main goal of this approach is to overcome the abstract characterization of populations and behaviors and to facilitate a more profound understanding of how agents react to policy interventions. It considers pre-existing behavioral attitudes, network effects, and social norms and proves to be crucial in establishing more informed projections about how individual and communal behaviors will transform in reaction to the outbreak and diffusion of an epidemic. By recognizing that agents are not merely virus carriers but also individuals with preferences and actions that have implications at multiple levels, the proposed approach addresses the need for greater nuance in both research and policy-making.

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