Perspective

Strategy evaluation and optimization with an artificial society toward a Pareto optimum

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Strategy evaluation and optimization in response to troubling urban issues has become a challenging issue due to increasing social uncertainty, unreliable predictions, and poor decision-making. To address this problem, we propose a universal computational experiment framework with a fine-grained artificial society that is integrated with data-based models. The purpose of the framework is to evaluate the consequences of various combinations of strategies geared towards reaching a Pareto optimum with regards to efficacy versus costs. As an example, by modeling coronavirus disease 2019 mitigation, we show that Pareto frontier nations could achieve better economic growth and more effective epidemic control through the analysis of real-world data. Our work suggests that a nation's intervention strategy could be optimized based on the measures adopted by Pareto frontier nations through large-scale computational experiments. Our solution has been validated for epidemic control, and it can be generalized to other urban issues as well.

Intractable urban issues, such as major epidemics, traffic congestion, environmental pollution, and imbalanced urban planning, pose a significant risk to citizens and a great burden to city governors. To deal with these issues, managers are implementing socio-technological advancements to transform their cities into smarter and more resilient areas through strategic optimization. Much exploratory work has been completed using parallel systems[1] to achieve effective city planning and management. However, current efforts are not enough to deal with these challenges. For instance, the contagion of the coronavirus disease 2019 (COVID-19) and its variants is still affecting the daily lives and economic activities of millions of individuals.[2] Therefore, the challenge of combining the latest techniques in the fields of machine learning, dynamic planning, and data mining with fine-grained artificial societies is an urgent problem to be solved, as it could lead to a pragmatic solution for strategy evaluation and optimization.

In this perspective, we uncovered the full potential of integrating data-analytical techniques and agent-based artificial society models. We designed a universal computational experiment framework for strategy evaluation and optimization when dealing with urban issues (shown in Figure 1). Firstly, in response to specific needs and problems (e.g., adjustment of epidemic control strategies), we used the agent-based modeling approach to build an artificial society corresponding to a real city. Secondly, the artificial society was driven by real-world data to conduct computational experiments. Using computational experiments, we designed rules for the combination and interaction of differing types of agents. Finally, we obtained various scenarios and ran them to produce complete scenario data. We modeled and analyzed these data with machine-learning or data-mining techniques.[3] Considering that decision-makers focus mainly on two indicators, cost (e.g., denoted by time or expenses) and efficacy, we aimed at customizing the data-based evaluation model toward a Pareto optimum. The best strategy was finally obtained based on evaluation under various scenarios. Next, we illustrated our solution by taking the containment of COVID-19 as an example.

Though governments around the world have adopted various interventions to contain COVID-19 transmission, individuals are still suffering from the effects of the epidemic.[4] Moreover, as the variants become more transmissible, precise prevention becomes more difficult, and the frequency of city lockdowns during emergencies increases, as seen in China. Despite China's success in containing COVID-19, the underlying heavy cost has stirred a global debate on whether these stringent measures were necessary. As a result, the question of what the optimal intervention strategy is urgently concerns decision-makers going forward.

DESIGNING A UNIVERSAL COMPUTATIONAL EXPERIMENT FRAMEWORK

In the framework, data models are responsible for calibrating the parameters of simulation models, providing prior information for calculations, and evaluating results after the simulation, while the fine-grained, agent-based artificial society provides a testbed to conduct epidemic simulations under complex scenarios at various spatial scales. The set of generated agents captures the average characteristics of the real population, which may change over time. The dynamic feature of the artificial society allows a more realistic analysis of an epidemic as well as a more informative evaluation of intervention strategies.[5] For instance, the artificial society can give information on the diagnosis of an individual (and their activity trajectory), the infection situation at a school or workplace, or the situation of an outbreak in a city.

We illustrated the strategy optimization process for containing the spread of COVID-19 as follows. Firstly, based on the intervention strategies collected from Pareto frontier nations (identified by real-world data analysis), an alternative strategy set was formed by further considering expert advice. Then, large-scale computational experiments were conducted on the alternative strategy set. Most measures were fixed, and then one or a combination of the measures (e.g., the starting time or the duration of the lockdown) were adjusted. Based on the evaluation results, the strategy that optimized pandemic control and economic growth simultaneously was found.

DEVELOPING DATA-BASED MODELS

Since CO_2 emissions were well modeled in previous studies that predicted gross domestic product (GDP) growth and incidence rates,[6–8] we built a predictive model using CO_2 emission data as a bridge connecting incidence rates with GDP loss. The model was validated by comparing our model output with the actual GDP percentage losses in four cities: there was about an 8.68% loss in Wuhan, a -2.90% loss in Beijing, a 2.29% loss in Guangzhou, and a 2.04% loss in Wenzhou. Moreover, we also modeled the governmental expenses for curing infected cases during the epidemic. With these models, we could evaluate the economic costs of interventions.

We developed a dynamic risk source model[9] to operationalize the risk emanating from an epicenter by using the relative difference between the predicted number of cumulative cases (with an estimation based on outbound flows to any prefectures) and the official reported data of COVID-19. The model not only forecast the distribution of confirmed cases but also identified regions with an elevated risk of transmission at an early stage. We used the generated risk score as warning information to aid the decision on whether more stringent measures should be adopted.

We have developed two data-based models for evaluating and assisting the optimization of interventions in the artificial society, respectively. The data models can also be adapted and replaced to suit the practical needs of different issues.

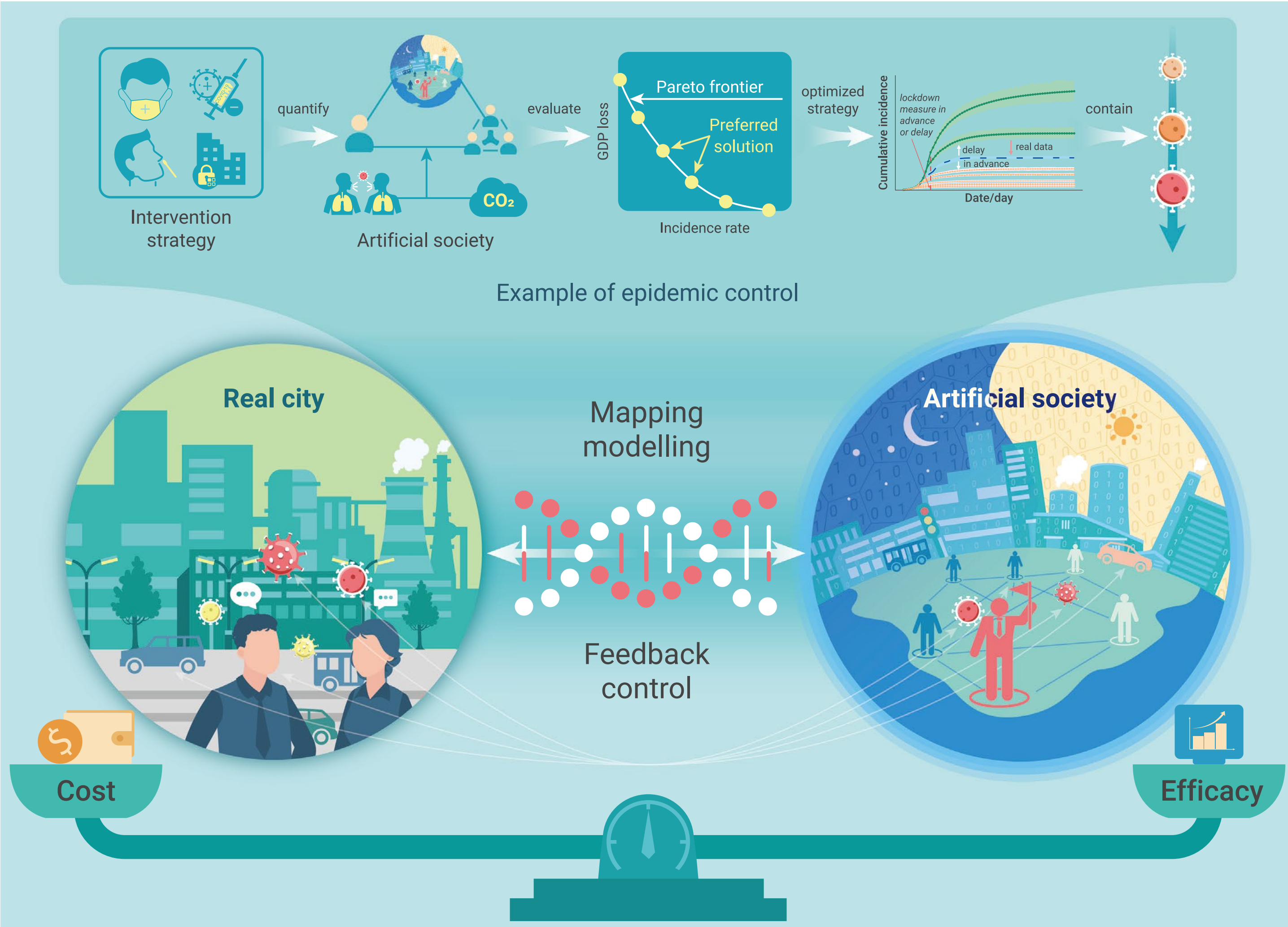

Figure 1. Overview of the proposed universal computational experiment framework for strategy evaluation and optimization in a fine-grained artificial society We took the containment of coronavirus disease 2019 as an example. The effectiveness of the proposed framework is validated by multi-source data during 2020 and 2021.

OPTIMIZING THE STRATEGIES TOWARDS A PARETO OPTIMUM

Based on the solution for strategy optimization, we first conducted a real-world data analysis by using the nondominated sorting genetic algorithm II[10] in over 62 countries and found a Pareto frontier among these countries in terms of optimizing pandemic control and economic growth simultaneously. Through analysis, we found that China and South Korea were on the Pareto frontier, indicating that their strategies showed advantages in balancing their economic growth and epidemic containment during 2020–2021. Moreover, we selected two other representative countries, i.e., the United States and the United Kingdom. After quantifying the intervention strategies of these countries, we compared their control efficacy and economic costs through large-scale computational experiments in a virtual artificial society under the same initial conditions. The Chinese strategy saved more than 22.3% in economic cost and reduced over 120 000 infection incidences compared with the United States strategy. However, the model showed that there is still room for improvement in the Chinese strategy.

Thus, we took the Chinese strategy as a benchmark and investigated when and to what extent the lockdown measures were necessary for a prefecture while keeping other measures the same. The results confirmed that in the context of emergencies, not only in terms of epidemic control but also in terms of economic benefits, the timing of lockdown measures in advance produced a superior outcome. Taking the counterfactual scenarios of Wenzhou as an example, if the lockdowns had been implemented once the risk index flagged high local transmission risks on January 27, 2020, the total number of confirmed cases in Wenzhou would have been reduced by ~90% and GDP losses would also have been reduced by 27.09% compared with what really happened. We conclude that in conjunction with the risk source model, adjusting the timing of the lockdown measures would allow for further optimization of the Chinese strategy.

DISCUSSION

In this work, we showed a new perspective on leveraging a universal computational experiment framework based on an artificial society to adjust strategies toward a Pareto optimum. Taking the mitigation of COVID-19 as an example, the proposed data models estimated the economic costs of an intervention strategy and quantified the risk of community transmission in a city. Our findings provide many implications for policymaking, two of which are as follows: (a) the artificial society could effectively support the adjustments of intervention strategies towards a Pareto optimum by taking the strategies of the Pareto frontier nations as a reference. (b) We verified that lockdown measures should be adopted in advance when the evaluated risk score is high and that these measures were effective and reduced economic costs regardless of the population size of a city. This point was also verified by a comparison between the epidemic control in Shenzhen and Shanghai from March 2022. There is no doubt that our perspective and methods can be applied to other areas of urban governance, such as traffic dispersion, emergency response, and environmental protection. We will explore these aspects in future work.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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