Can Agent-Based Modeling Enable Scientific Policy Making Based on an Understanding of Causal Mechanisms?

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¿Puede el modelado basado en agentes permitir la formulación de políticas científicas basadas en la comprensión de los mecanismos causales?

Palabras clave: modelado basado en agentes, política científica, mecanismos causales, sistemas sociales

基于agent模型能在理解因果机制的基础上让科学决策成为可能吗？

关键词：基于agent建模，科学政策，因果机制，社会系统

Many social problems depend on government policy. In democratic societies, government policy should essentially aim to allow people of all levels to lead spiritually- and materially-rich and safe lives. However, this is not the case in reality. Most countries have various social problems, including remarkable wealth inequality between rich and poor and the issue of social welfare, which appear to be becoming increasingly serious. Underlying these problems is the fact that the true causal mechanisms of var-

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ious phenomena in society are not well understood or shared among people, and the policy-making process is likely to be designed for those who have vested interests or powers. It is therefore desirable to correctly understand the causal mechanisms underlying the emergence of social and economic phenomena, based on which social and economic policy by the government is scientifically backed.

In both natural and social systems, there exists a cause and causal mechanism for the occurrence of each phenomenon. In the fields of natural science and engineering, hypotheses and equation-based models concerning these causal mechanisms have been proposed based on observation of the behavior of various phenomena, which are verified by a series of controlled experiments. Thus, natural science and engineering comprise accumulated knowledge and data on the causal mechanisms of various phenomena. The background that various hypotheses have been proved by experiments, owing to which the causal mechanism of each phenomenon has been clarified, is that natural phenomena' behavior is universal and unchanged over time and space. For example, the light speed is constant and does not change with place or time. The same is true for various laws of nature. Because of this principle, hypotheses concerning causal mechanisms could be proved true or not by researchers worldwide without depending on the time and space.

Conversely, in the fields of social science and economics, various phenomena are caused by decision-makers' behaviors and their interactions, which change with time and place and depend on the heterogeneity of individual intentions. In principle, it is therefore impossible to conduct controlled experiments such as those for natural phenomena in the social world. This implies that a traditional approach is in principle insufficient to clarify the causal mechanism of social phenomena. Furthermore, the causal mechanisms between the causes and effects related to social phenomena are complicated because the human behavior that causes changes in the state of society depends on the state of society itself, and the manner of dependence varies across individuals; therefore, there is a limit to expressing such mechanisms with a simple set of equations.

Agent-based modeling (ABM) is a powerful approach for elucidating the causal mechanisms of social phenomena. ABM is a method where an artificial society is constructed using a computer, based on assuming the actions of multiple decision-makers and reproducing the emergence of various macro phenomena. If the assumed input conditions do not include macro factors other than the behavior of the decision-maker (i.e., if the model is 100% bottom-up), it is, in principle, possible to build a model so that the causal relationship emergent in the artificial society could be same as that in the actual system.

The history of ABM dates back to John von Neumann's theory of "self-reproducing automaton" (1966). Cellular automata devised based on this theory are considered to provide the roots of

ABM. One of the earliest models was Thomas Schelling's ethnic segregation model (1971). Subsequently, "Growing Artificial Societies" written by J. M. Epstein and R. Axtell (1996) and "Simulation for the Social Scientist" by N. Gilbert and K. G. Troitzsch (2005) were published. In these books, the ideas of building a model by abstracting the real world to some extent and that a model can be roughly classified into abstract, middle range, and facsimile models in terms of the degree of precision were proposed. However, criticisms regarding the validity of ABM have been reported, including the argument that ABM cannot specify the necessary conditions for reproducing a specific macro phenomenon because of its inherent functional complexity (R. E. Marks, 2007). Therefore, many researchers seem to consider that although ABM is effective in offering hints on the emergent mechanisms of phenomena in the real world, it is not sufficiently reliable for elucidating the causal mechanisms to replace the traditional approach of economics. ABM has so far received little recognition as a promising methodology that can be used for deciding public policies, except for one paper entitled, "Economy needs agent-based modeling" by J.D.Farmer et al. (2009).

However, as many modelers have probably experienced, ABM emerges different macro phenomena with different input conditions that are assumed. It is also noted that not all factors of the input condition change the characteristics of the macro phenomenon that is the output. Among the factors for a certain input condition, the set of factors indispensable for the emergence of the macro phenomenon are considered the cause of the macro phenomenon in question; therefore, there is a causal relationship between the input condition that consists of a set of indispensable factors and the macro phenomenon. In this context, the input condition comprises the types of agents, their behavioral rules, and attribute variables. Because the combination of these factors can provide a model structure simulating a real system, the input condition will be referred to as a model structure below.

If we perform a series of computer experiments that systematically change the model structure and elucidate the structure that is indispensable for reproducing the characteristics of a macro phenomenon observed in the real world, the causal relationship between the model structure and the macro phenomenon clarified in the model can be considered to represent the causal relationship in the real world. Next, by considering the reason why factors in the model structure clarified by computer experiments are indispensable, it is possible to gain a better understanding of the causal mechanism of that phenomenon.

The author has found that there are indispensable model structures for reproducing various socio-economic phenomena. Considering why the model structure was indispensable confirmed that the extracted causal mechanism was reasonable. Shown below are some research examples.

First, to reproduce the equilibrium of the prices in a goods market,

indispensable factors are: (1) consumer's low price-oriented consumption behaviors and (2) producer's inventory management-oriented determination behaviors of production volume and price. Next, to reproduce the business cycle (i.e., the periodic fluctuation of gross domestic product (GDP)), indispensable factors in addition to (1) and (2) above are the following four factors: (3) producer's judgment for investment based on demand forecast for the expansion of production capacity, (4) producer's wage-increasing behavior when profits are increased, (5) producer's bank financing for investment (i.e., credit creation), and (6) the existence of an upper limit on credit creation. Conditions (3) and (4) imply the existence of productivity improvement and the accompanying increase in wages. Conditions (5) and (6) imply the existence of funds that need to be repaid. In other words, when funds are supplied to the market by bank borrowing, the economy expands because of a virtuous cycle of increased investment, wages, and demand. When borrowing becomes excessive, the amount of funds returned to banks exceeds the amount of borrowed funds, and funds are absorbed from the market to banks. The economy, therefore, declines because of a vicious cycle of reduced investment, lower wages, and lower demand.

In addition to the above, the indispensable model structures for income tax cuts and corporate tax cuts to increase GDP have also been studied. The indispensable model structure to reproduce the positive effect of income tax reduction on GDP is the inclusion of inefficiency in government expenditure in addition to the factors described above. Here, government spending inefficiency is defined in the model as the ratio of firm subsidy to total expenditure, where firm subsidies are funds that the government unnecessarily and sometimes unintentionally distributes to business sectors without expecting their economic value. In the case of households, the inefficiency in expenditure corresponds to one minus marginal propensity to consume. The research result indicates that income tax reduction increases GDP only when government expenditure inefficiency is more significant than that of the household. This implies that the household's funds raised by income tax reduction are more effectively consumed in the market than the government's case. The indispensable factors to reproduce the positive effect of corporate tax reduction are, in addition to the inefficiency in government expenditure, the existence of executive compensation, financing for investment from internal funds as well as from the bank, and mitigation of credit restriction. These are the factors that realize that the funds distributed to firms by corporate tax reduction are more effectively consumed in the market in the form of executives' consumption and firms' investment than the case owned by the government.

In summary, the indispensable model structure elucidated by a series of computer experiments indicates the mechanism of tax cuts' effect is as follows. The income tax cuts and corporate tax cuts increase GDP when the government's funds supplied to the

private sector through tax cuts increase demand in the market through the private sector's investment and consumption, which seems reasonable. Factors related to the labor market, such as corporate bankruptcy and the unemployment rate, are not indispensable factors for reproducing the effect of the corporate tax cut.

Another example is the indispensable model structure for the bullying phenomenon. The macro phenomenon observed in the bullying phenomenon is the emergence of five groups: bullies, the bullied, complete bystanders, persons who go along with the bullies, and those with the bullied. The indispensable model structure for the emergence of these five groups is as follows: (1) People tend to tune with and exclude others; these tendencies vary from agent to agent and unique to each agent; (2) The act of excluding others is performed only if the opponent is weaker than the agent. Furthermore, analysis of the frequency of exclusion and being excluded suggests that those with a strong tendency to bully others are those with strong tendencies to tune with others and exclude others. Those who are more likely to be bullied have a weak tendency to tune with others and a weak tendency to exclude others. These results are generally consistent with previous research based on questionnaires and similar approaches reported so far and are considered a reasonable mechanism.

Recently, the author constructed an ABM model for corona infection. The feature of this model is that it considers not only the contact infection of people, but also the number of viruses, virus elimination by immunity, and enhancement of immunity by antibody production. The latter factors are the factors involved in the recovery process. Determining the model structure based on medical knowledge confirmed that this model successfully reproduced expansion and convergence of the pandemic and features of time differences of the accompanying peaks in the number of newly infected persons, the number of newly recovered persons, and the number of infected persons. This model assumed that the number of viruses eliminated in each period by immunity was proportional to the number of viruses in the body. Here, if the number of viruses eliminated in each period is assumed to be a constant value, then the number of newly recovered persons does not exceed the number of newly infected persons, and therefore the pandemic does not converge. That is, the assumption that the number of viruses eliminated from the body by immunity increases with the increasing number of viruses in the body appears to be indispensable for reproducing the convergence of the pandemic. This assumption corresponds with the fact that if the viruses enter the body because of infection, the body temperature rises and immunity increases accordingly. The literature shows that a 1° C increase in body temperature increases immunity five-fold. For this reason, it is important to distinguish infected persons from healthy persons, and suppress the frequency of contact between the two groups to prevent the spread of

infection. Monitoring body temperature is effective in addition to PCR tests (Polymer Chain Reaction test) to identify infected persons because body temperature might sensitively rise even if the number of viruses entered into the body is small.

As shown in the above example, it is possible for ABM to identify an indispensable model structure for reproducing the macro phenomenon observed in the real system by a series of computer experiments in which input conditions are systematically changed. Then, by considering the reason why the model structure is indispensable, we can gain a better understanding of the causal mechanism of various phenomena in society.

The validity of ABM has been argued since its development, but it is considered possible to use ABM to accumulate knowledge on the causal mechanism of specific socio-economic macro phenomenon by clarifying the model structure that is indispensable for reproducing the qualitative characteristics of that phenomenon. By accumulating such knowledge, it may be believable that social science and economics will become a system of truth related to the causal mechanism of the behavior of the socio-economic system, not just a set of theories. In further application, the same approach will enable quantitative reproduction of macro phenomena. When reproducing the quantitative characteristics of macro phenomena with a model, the combination of the numerical values of the attribute variables included in the input conditions needs to be clarified by a series of computer experiments based on the indispensable model structure for the qualitative reproduction of the phenomenon. In this context, numerical values can be represented by relative numerical values, such as the ratio to a specific reference value. Such a specific reference value includes the total population and total amount of funds in the system.

This principle of ABM for elucidating the causal mechanism mentioned above is considered applicable even for the biological system, including the human disease phenomenon. In the human body, various symptoms accompanied by disease correspond to the characteristics of the macro phenomenon. The behaviors of internal organs or cells may be the input condition for the emergence of various diseases. The causal mechanism could be clarified by the same procedure mentioned above. First, a model should be constructed with the assumption based on the medical knowledge on the disease's emergence as precisely as possible. A set of indispensable factors to reproduce the emergence of a particular disease should be clarified by a series of computer experiments. By considering why such a set of factors is essential for the emergence of the disease symptoms, it might be possible to better understand the causal mechanism of the disease's emergence. This approach may complement the medical approach because the human body is a complex system. The traditional method may have a limit to some extent in clarifying the causal mechanism of the diseases.

In the policy-making process, it is possible to determine effective policies by a set of "what-if" analyses by predicting the effect of the policies included in the input conditions using the model structure clarified for each macro phenomenon. This approach will contribute to constructing a truly democratic society for all.