Artificial Societies, Computational Experiments, and Parallel Systems: An Investigation on a Computational Theory for Complex Socioeconomic Systems

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Artificial Societies, Computational Experiments, and Parallel Systems: An Investigation on a Computational Theory for Complex Socio-Economic Systems

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Abstract—This paper addresses issues related to the development of a computational theory and corresponding methods for studying complex socio-economic systems. We propose a novel computational framework called ACP (Artificial societies, Computational experiments and Parallel systems), targeting at creating an effective computational theory and developing a systematic methodological framework for socio-economic studies. The basic idea behind the ACP approach is: 1) to model the complex socio-economic systems as artificial societies using agent techniques in a "bottom-up" fashion; 2) to utilize innovative computing technologies and make computers as experimental laboratories for investigating socio-economic problems; and 3) to achieve an effective management and control of the focal complex socio-economic system through parallel executions between artificial and actual socio-economic systems. An ACP-based experimental platform called MacroEconSim has been discussed, which can be used for modeling, analyzing and experimenting on macro-economic systems. A case study on economic inflation is also presented to illustrate the key research areas and algorithms integrated in this platform.

Index Terms—Artificial Societies, Computational Experiments, Parallel Systems, Socio-economic Systems

1 INTRODUCTION

EXPERIMENTAL economics [1] and computational experiments [2] are two important directions in socio-economic studies. In particular, Prescott and Kydland were the first to propose the computational experiment as a new method in addressing economic issues, and discussed related questions in business cycle research using computational experiments [3]. As such, experimentation methods, whether as a direct way in real world or an indirect way on the computer, have attracted much more attention from economists [4-6].

In this paper, we will discuss how to use the new theory and related computational methods in complex systems research [7], so as to integrate the experimental economics methods and the computational experiment methods, and merge the artificial societies, computational experiments and parallel systems (so-called ACP approach) to form a novel computational framework in solving complex socio-economic problems.

Early in 1970s, Shoven and Whally used the Model Economics and computational experiment methods to estimate the quantitative effects of free trade policies, evaluate the welfare effect resulting from changes in the tax systems, and quantify the magnitude and nature of business cycle fluctuations induced by different stocks, and so on [8, 9]. In mid-1990s, Kydland and Prescott proposed that computational experiment can be applied as a valuable economic tool [3]. Although much attention has been paid on computational experiment in economic research, the following problems of computational experiments in economics are still unsolved from the perspective of modern computing method and complex systems theory [10~15].

1) Many economic models are still static and based on linear extrapolation. However, complex socio-economic systems are inherently dynamic and non-linear, so that traditional approaches such as linear extrapolation are no longer suitable.

2) Most of the models are based on integrating the existing economic theories, targeting at simulating and approximating the real economic systems. In fact, there are as yet no effective, widely accepted methods for modeling complex socio-economic systems, especially those involving human behaviors and social organizations [16]. Further, in many cases such as emergency response, imaginary scenarios are also important and should be considered real – an alternative possible realization of target systems.

3) Computational experiments are mostly used for economic analysis or off-line decision support and analysis, instead of real-time online decision-making and analysis. Especially, in almost all cases, proposed and used computational experiments are no different from traditional computer simulations.

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The concept of artificial societies opens up a new way for reevaluating the computational experiment method and its applications. This concept was proposed in the early 1990s by Builder and Bankes from the RAND Corporation in U.S. [17], and was used for studying the social impact of information technology. With computer-generated artificial societies, we can study the impacts of different information technologies, facilities and capabilities on them. In traditional simulation of societies, the actual society is regarded as the only real existence and the only reference and standard to evaluate the experimental results. On the contrary, artificial society simulation has evolved to the level of "multiple societies", in which the artificial societies are regarded as possible alternative forms of the real society [18, 19]. This novel understanding of artificial societies has emerged after the integration of artificial life [20] and artificial society [18~22].

The artificial society method provides the basis for the re-examination of computational experiments, and it is also the starting point for applying theories and methods of computational experiments to re-think and re-understand various socio-economic issues [21]. Economic models in computational experiments are no longer exclusively a combination of existing economic theories or models, but the specific economic societies "generated" by the related behavior of human and social organizations. The behavior can be summarized or deduced from the real world, and also can be completely assumed or specified. Model Economy based on this viewpoint is a proactive, integrated, and bottom-up research approach, which can "foster and grow" economic systems using computers and agent-based programming, simulate the characteristics and development features of artificial economic systems. The traditional Model Economy studies a system through its related subsystems, and uses computers and numerical technology to construct, integrate, simulate and retrospect the various states and development features of real economic systems. Thus, it is a passive, regressive and top-down research method. The research on artificial stock markets can be considered as one of the first attempts to study economic systems from the perspective of artificial societies [23]. Computational experiments based on artificial society models can obtain similar analysis as from traditional methods, and can also provide a new method for the research and analysis of the subjectivity, possibility and psychological effects in socio-economic systems.

Based on this new understanding of computational experiments, we can further introduce the management of complex systems and parallel systems method from cybernetics into socio-economic decision analysis, support and generation [22]. In other words, we can formulate an artificial socio-economic system based on an artificial society, and combined this artificial entity with the real socio-economic system. The two systems can be regarded as a single parallel system, with which we can conduct various computations and experiments to analyze different socio-economic policies. This can help us make decisions and also support their evaluation and implementation. The emergence of modern large-scale computing methods, especially the cloud computing and Internet of things [24, 25], lays the technical foundation for carrying out the proposed parallel systems method.

We believe that the ACP approach, that is, the integration of artificial societies for modeling, computational experiments for analysis and evaluation, and parallel systems for control and management, forms a theoretical and methodological framework for studying complex systems in a computational way, and can be especiallly effective in solving socio-economic problems. We should spend more efforts along the direction of this ACP framework, and combine it with traditional socio-economic analysis and in particular the Hall for Workshop of Metasynthetic Engineering (HWME) proposed by Chinese researchers [26, 27].

The purpose of this paper is to stimulate more research efforts in applying this proposed ACP-based computational theory and corresponding methods in issues related to complex socio-economic systems. The remainder of this paper is organized as follows. Section 2 presents the basic hypotheses and key problems in the ACP-based computational theory of socio-economic systems. In Section 3, 4 and 5, we discuss in detail agent-based modeling of artificial societies, computational experiment methods and the rationale for parallel execution, respectively. Section 6 presents an ACP-based platform dedicated to macro-economic research, and a case study on inflation. In the end, we conclude our efforts in Section 7 and discuss some potential research directions in future works.

2 Basic Hypotheses and Key Problems in ACP-Based Computational Theory of Socio-Economic Systems

Basic hypotheses and key problems in a computational theory for socio-economic systems are similar to those for general complex systems. Therefore, based on the computational theory for complex systems [7], we focus on two basic hypotheses on complex socio-economic systems.

Hypothesis 1: Intrinsically, the overall behavior of the complex socio-economic systems cannot be determined through the independent analysis of their components.

Hypothesis 2: Intrinsically, the overall behavior of the complex socio-economic systems cannot be determined in advance in large-scale of time, space or other dimensions.

Currently, Hypothesis 1 has become a common sense in researchers on complex systems. Hypothesis 2, however, is controversial, and even is regarded as the results of agnosticism by some researchers [7].

As a consensus, hypothesis 1 established the core position of the holism instead of reductionism in the research of socio-economic systems. Hypothesis 2 made the possibility, instead of certainty, become a major characteristic to describe complex socio-economic systems. Based on these two hypotheses, we can obtain the following corollaries.

1) It is necessary to consider the complex socio-economic problems from the viewpoint of holism. Previous system analysis methods usually can not characterize the relationships among different components of systems due to undefined system structures and uncertain boundaries. Therefore, we must explore new approaches for complex socio-economic systems based on existing works. The research method based on artificial societies is very useful for this purpose [18, 19].

2) It is impossible for seeking a "once-for-all" solution to all problems in complex socio-economic systems. Especially, these systems are changing dynamically, and the problems are also changing and developing. Thus, the cognition process needs to be deepened progressively, so that there does not exist an accurate, complete and overall model for analyzing such systems. Therefore, we need to establish an effective and feasible framework of computational experiments [19, 21], and then improve the solutions to complex socio-economic systems progressively with computational experiments.

3) There is no unique optimal solution for problems in complex socio-economic systems. First, the optimal solution of an analytical model is related directly to the assumptions, which usually have strong conditional sensitivity. In complex socio-economic systems, however, the assumptions are usually different with the actual situations, so that a small error may lead to a big discrepancy in the final results. Second, there generally does not exist a single objective or index for optimization in solving problems in complex socio-economic systems, while multi-objective or multi-level optimization typically leads to multiple or even infinite solutions. Furthermore, it is even difficult to determine proper indices for optimizing such systems. Therefore, we should accept the concept of effective or satisfying solutions, and also the fact that there might be many effective solutions in general. As such, we should use the parallel systems approach by considering both artificial systems and real systems [22] to seek for effective and dynamically self-adaptive solutions.

Based on the above corollaries, we should follow the "trail and error" principle to seek for effective solutions and establish novel research frameworks for complex socio-economic systems. We should establish a scientific, systematic and comprehensive framework by using the ACP approach (that is, artificial societies, computational experiments and parallel systems methods), as well as parallel and distributed computing techniques [26, 27].

Based on agent-based artificial societies and complex systems theory, we can systematically investigate the major issues in complex socio-economic systems with computational experiments and parallel systems. We will focus on solving the following key problems.

1) Modeling: how to construct comprehensive artificial societies in a bottom-up fashion, based on the principles of "agreeable on simple" by starting from the consistence and difference among simple objects and their interactions, and considering the nature of proactivity and randomness of simple objects.

2) Experimentation: how to use artificial societies to generate and analyze behaviors of complex socio-economic systems, and then establish a theory and method for computational experiments through computing, simulating, emergence, and observation. This can offer a way to overcome the difficulties of conducting experiments on complex systems, and lay a foundation for testing the consequence of possible actions and evaluating the effect of decisions effectively on complex socio-economic systems.

3) Decision-making: how to use artificial societies and computational experiments in constructing parallel systems for decision-making through the interaction between real and artificial societies. By comparison, leaning and experimentation with parallel systems, we can achieve the intelligent management and control for complex socio-economic systems.

4) Computing: how to utilize networked high performance computing and sensing environments, such as cloud computing and cyber-physical systems, for the generation and evolution of complex artificial societies in a bottom-up, reliable, effective and low-cost fashion. In order to support the implementation of computational experiments and parallel systems in various applications, we must address issues related to transportability, extendibility and interchangeability.

The purpose for solving these key problems is to establish a systematic and comprehensive basic framework and develop related key methods for complex socio-economic system studies, and build corresponding computing platforms for specific applications.

3 Modeling Complex Systems with Artificial Societies

In most researches for physical systems, models are built to describe actions and responses of target systems. With such models, we can achieve various objectives, including the design, analysis, control and synthesis of real systems. Commonly, the most essential requirement of modeling is that, the final model must be as close as possible to a real system. Thus, the real system is the only reference and standard. For most physical systems, if their responses are predictable, we can find a way to manage or regulate those systems based on conventional control theories.

However, there are as yet no effective, widely accepted methods for modeling complex systems, especially those involving human behaviors and social organizations [16]. Socio-economic systems are typical ones. Although there have existed many economic models, we are still not capable of describing precisely the responses of a complex economic system. In the past, the hope is to find a way that enables us to divide a complex system into simpler sub-systems and build an exact model for each subsystem, and then synthesize them back into the original complex system. However, this approach conflicts directly with our Hypothesis 1, we have to seek an alternative path. So far, agent-based artificial societies or general artificial systems might be the most promising path for this consideration [28~31].

Although the theory and implement of artificial societies are still at their preliminary stage, some of their characteristics have offered many advantages for modeling complex socio-economic systems. For examples:

1) Instead of isolating components in complex systems, artificial societies emphasize the importance of interactivities, inter-relationship, and integration amomg them.

2) By using artificial systems in real, simulated or mixed environments, this approach can generate complex interactions and behavior patterns. As a result, we can observe, analyze and understand complex systems through emergences.

With these characteristics, especially the second characteristic, artificial societies approach can adapt complex features of socio-economic systems, thus support various controllable and precise computational experiments in a manipulated manner, so as to quantitatively analyze and evaluate different behaviors as well as different influence factors. That is the main target of using artificial societies in studying socio-economic systems. In other words, articical societies are our experimental lab, although computational, for socio-economic studies.

Modeling with artificial societies normally consists of three main parts: agents, environments, and rules for interactions. In this approach, the accuracy of approximation to the real systems is no longer the only objective, as it is in traditional computer simulations. Instead, the model represented by an artificial system is considered real - an alternative possible realization of the target system. Along this line of thinking, the real society is also one possible realization. Thus, the behaviors of two societies, real and artificial, are different but considered equivalent for evaluation and analysis.

In addition, modeling with artificial societies does not exclude the exact description of target systems. Actually, approximation with high accuracy is still the desired goal. The idea of equivalent behaviors is a forced compromise that recognizes intrinsic limits and constraints when dealing with complex systems, as imposed by our two Hypotheses stated in the beginning of Section 2.

4 Computational Experiments: From System Simulation to System Experimentation

As is well known, the research objects in socio-economic systems normally cannot be "tested", let alone be "experimented" or "repeatedly tested". As such, it is usually more difficult for researchers to study complex socio-economic systems than conventional systems. Even if such a test can be conducted, there might be subjective and uncontrollable influencing factors involved, so that the results and conclusions cannot be generalized. Generally speaking, there are four aspects involved in this difficulty.

First, just as is pointed out by H. Simon, we cannot conduct traditional reductive analysis on the decomposed socio-economic systems, which in essence have lost the functionalities and effects of the original systems [32].

Second, we usually cannot afford the large experimental costs due to the size of complex socio-economic systems.

Third, many complex socio-economic systems are related to such issues as national defense, military combat readiness and social security, so that we cannot legally experiment on these protected systems.

Fourth, large numbers of people are typically involved in complex socio-economic systems, thus experiments on them might possibly incur life and property losses, or at least affect their normal lives, therefore are morally unacceptable.

As such, solving the "test" or "experimentation" problems in complex socio-economic systems can be considered as one of the key research issues in complex systems research.

Computer simulation has long been used in economics research, and a great deal of related works has been conducted with simulation to experimentally evaluate various economic policies. Many consider the integration of computer simulation and economics modeling as a form of experiments, called computational experiments [3]. Traditionally, such computational experiments include the following five steps.

First, posing economic problems. The purpose of a computational experiment is to derive a quatitative answer to some well-defined problems in a specific domain. Thus, the first step in conducting a computational experiment is to pose such economic problems.

Second, using well-tested theory. Once economic problems are posed, some strong theories that have been tested and found to provide reliable answers are needed to carry out computational experiments.

Third, constructing a model economy. In this step, the key issues are determining the modeling details and the feasibility of computing the equilibrium process.

Fouth, calibrating the model economy. The process and objective of calibrating the model economy is quite similar to that of calibrating physical measurement systems. Generally, some economic problems have known answers. Only when the model economy can give an approximately correct answer to these problems, can we be confident to solve novel economic problems with it. Therefore, data must be used to calibrate the model economy so that it mimics the world as closely as possible along a limited, but clearly specified, number of dimensions.

Fifth, running the computational experiments. Quantitative economic theory uses theory and measurement to estimate the scales of problems. The instrument is a computer program that determines the equilibirum process of the model economy and uses this equilibrium process to generate equilibrium realizations of the model economy. The computational experiment is the process of using this instrument. These equilibrium realizations of the model economy can be compared with the behavior of the actual economy in some periods.

Therefore, the computational experiment currently used in economics is not exactly the same as, and can only be a part of the one in complex systems research [20]. Moreover, such computational experiment aims exclusively at approaching the real world as closely as possible. The major methodology is numerical-calculus-based mathematical equations, while the agent-based and behavior-based artificial society methods are not involved.

Due to the urgent requirements from complex systems research, simulation has no longer been limited to differential and difference equations. Behavioral simulation on dynamic discrete events and hybrid systems has attracted much more academic attention [33]. The emergence of artificial life and artificial society instills new vitality to simulation research from the perspectives of ideology and methodology. Nowadays, many simulation approaches and frameworks, such as parallel computing, distributed computing and grid computing, have been widely used. As a result, simulation can develop from natural process simulation based on differential and difference equations, to computational simulation on artificial or hybrid processes such as social systems and human behavior. Moreover, due to the inherent subjectivity of complex systems with society and human, we can further consider that, the simulation result is an alternative version of reality, and the real system is one of the possible kinds of reality. This idea leads to the evolution from system simulation to computational experiment.

In computational experiments, traditional computer simulation can be considered as a test process in "computer laboratory" and an approach of "evolving" diverse complex socio-economic systems as well. The real system is only a possible result of the computational experiments. Therefore, unlike that the real system is used in computational simulation as a unique reference and standard to evaluate the simulation results, computational simulation is regarded as a possible implementation and alternative version of the real system in computational experiments. As such, we can naturally use computational simulation in computational experiments.

Computational experiment is largely the same as the research approach of artificial life and artificial society. The computational simulation of experimental systems is mainly based on agent technique and object-oriented programming. The basic idea is to create artificial objects, and proactively generate diverse behavior of the experimental systems in a bottom-up fashion through the interactions of artificial objects. Meanwhile, the influence of various factors on these behaviors must be taken into consideration, so that simulations should be conducted on the overall system behavior. This is quite different from computational simulations in which only a part of the system behavior can be simulated.

The major reasons for the evolution from system simulation to computational experiment can be summarized as follows:

First, computational experiment is a beneficial attempt to overcome the difficulties in experimenting on complex systems, especially complex socio-economic systems.

Second, the increasing computational capabilities (especially the maturity and popularity of parallel computing, distributed computing, grid computing and even the future quantum computing) , as well as the emerging and developing analysis and modeling approaches, have provided sufficient technical supports to computational experiment.

Third, researchers used to believe that computational simulations cannot replace real experiments, since the simulated objects are typically unique and objective natural processes that can be experimented repeatedly. However, in computational experiments, the experimented objects are not unique, and many subjective factors might be involved in understanding their behaviors. Therefore, it can be easily accepted that computational simulation can be used as an alternative version or a possible implementation of reality.

Fourth, in computational experiments, artificial objects are created with the "bottom-up" agent technique, and interact to generate experiment results. Although inconsistences usually appear in understanding the overall behavior in complex socio-economic systems, consensuses can be easily reached in understanding the local behavior of simple artificial objects. As such, the complex behavior emerged from the local behavior can also be easily understood and accepted.

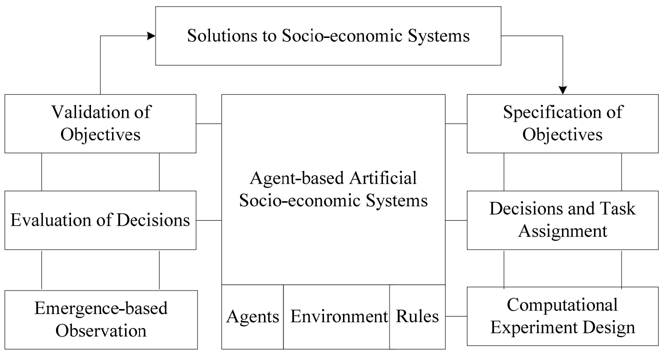

Fig. 1. Computational Experiment, Behavior Analysis and Decision Evaluation based on Artificial Socio-economic Systems

Figure 1 shows the process of analyzing and evaluating the solutions to complex systems using computational experiments, in which emergence plays a key role. Various complex phenomena, such as self-learning, self-adaptation, and self-organization, can “grow” from artificial society by means of emergence.

We can analyze and evaluate various solutions to complex socio-economic systems by designing different experiment scenarios in artificial society, possibly with large numbers of repetitions when necessary. Due to the lack of sufficient observing time and obtained data, it is usually very difficult in real systems to conduct these accurate, reliable and quantitative analyses and evaluations. Specially, artificial society is not only a simulated version of reality, but also can provide various alternative versions of the real society. This can greatly extend the applicability of quantitative analysis and the robustness of the results.

Moreover, we can conduct accelerated experiments, stressing experiments and limit experiments on the performance, reliability and quality of solutions to complex systems, based on designability and repeatability of computational experiments in artificial societies. These experiments are generally not allowed to be conducted directly in the real systems, especially those working systems.

5 Parallel Systems: Coevolving Artificial Societies and Real Societies

Parallel systems refer to one or more artificial systems running in parallel with a real system. In fact, the modern control theories are successful applications of parallel systems. The classic transfer function, the state space approach, the optimal control theory, the parametric recognition and the adaptive control, especially the model reference adaptive control [34], are essentially particular applications of parallel systems. In common control systems, decisions and operations are targeted at the real systems, and seldom at the artificial systems. Since we can analyze, predict and control the real systems with sufficiently precise mathematical models, it's unnecessary to study the artificial models and systems. Actually, the models (i.e. artificial societies) are passively used in the control of the real systems, so it's impossible to control the artificial systems.

In the complex systems study, we commonly have few mathematical models which are sufficiently precise for the real systems, so we can hardly establish models to predict short-term actions of the target systems. Hence, we must try to explore the potential of artificial systems in parallel systems, transform the role of artificial systems from offline to online, from static to dynamic, and from passive to proactive, so as to make them play equivalent roles as the real systems.

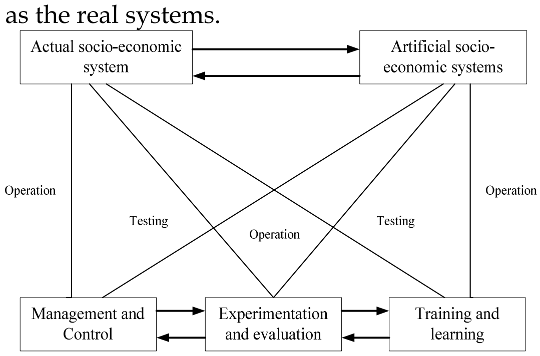

Fig. 2. Parallel Systems for Control and Management of Socio-Economic Systems

The major objective of the parallel system is to interact, analyze and compare artificial and real systems, so as to achieve the prediction and evaluation for each system. Such parallel system provides a mechanism for the study, management and control of complex systems. Figure 2 illustrates the basic framework for applying parallel systems in the complex economic system study, involving three major modes of operations:

1) Experimentation and evaluation. In this operation, artificial economic systems are mainly used to conduct computational experiments, which analyze and reveal various behaviors and responses of the complex systems. Sequentially, different solutions are evaluated to support the decision making. For this purpose, the connections between parallel systems are on and off alternatively.

2) Learning and training. In this operation, artificial economic systems are mainly used as a center for learning and training the control and management of the complex systems [10]. Normally, real and artificial systems are disconnected.

3) Control and management. In this operation, artificial economic systems try to emulate the real system, such that we can use the emerging behaviors to improve and optimize the real system's performance in real time. Moreover, through observing differences of the evaluated states between the artificial systems and the real system, we can improve the evaluation of the artificial systems and adjust their parameters.

Generally, methods and algorithms developed in simulation-based optimization and adaptive control, such as rolling-horizon analysis and model-reference feedback control, could be used in parallel systems.

6 Socio-Economic Experimental Platform and Case Studies

Socio-economic systems are typically complex giant systems, in which there exist large numbers of microscopic social individuals with such properties as dynamics, limited rationality, constrained interactions, and self-adaptive learning. Therefore, it is difficult to mathematically analyze and computationally evaluate the macroscopic socio-economic systems. The emergence of social computing and ACP approach provides a set of computable, implementable and comparable theories and methods for systematically studying complex socio-economic issues [16, 35].

6.1 The MacroEconSim Platform

Based on the ACP approach, we have developed a macro-economic computational experiment platform (MacroEconSim for short), aiming to support the modeling, experimentation, management and control of complex macro-economic systems. Figure 3 shows a detailed roadmap for macro-economic research based on MacroEconSim platform.

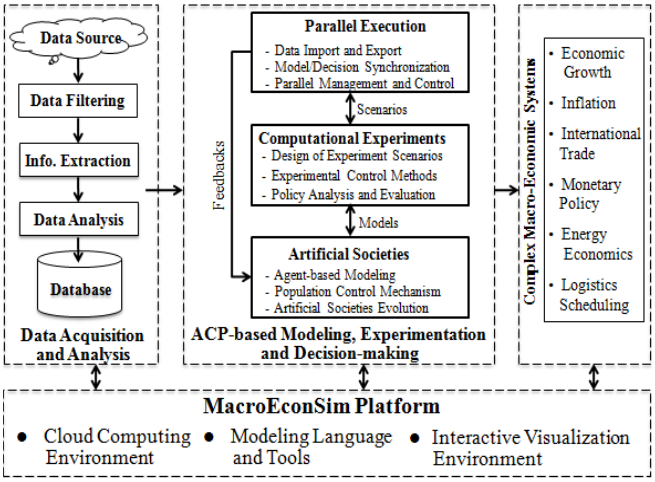

Fig. 3. Roadmap for Macro-Economic Research with MacroEconSim Platform

1) Artificial Soceities: MacroEconSim platform provides agent-based toolkits for modeling the participants and environments (including organizations, policies and events) of complex macro-economic systems, and can evolve large numbers of agents acting on behalf of the participants according to specific population growth and control mechanisms.

2) Computational Experiments: MacroEconSim platform provides high-level application programming interfaces (API) to facilitate users to design precise and controllable experiment scenarios, so as to quantitatively analyze and evaluate various influential factors and parameters in macro-economic systems.

3) Parallel Executions: MacroEconSim platform has incorporated such techniques as deep-web data mining and open-source data acquisition to monitor the global macro-economic data in real time. In this way, we can realize the synchronization on data, models and decisions between the real and artificial macro-economic systems, and thus support the monitoring, early warning, and decision-making for macro-economic systems.

MacroEconSim platform consists of components including an artificial society, simulation systems, decision center and control center. Large numbers of artificial agents interact with each other in the platform on behalf of their participants. These agents are classified into multiple simulation systems, which are oriented to specific macro-economic topics and experiment scenarios. These simulation systems co-evolve with the real-world system based on the parallel execution mechanism. Meanwhile, user-defined experiment scenarios are also allowed to be uploaded to the platform, and will be controlled by the decision center and control center to help analyze, evaluate and optimize various parameters in macro-economic systems.

MacroEconSim is now deployed on the "intelligent cloud computing platform" developed by Institute of Automation in Chinese Academy of Sciences. Distributed techniques, such as nosql and map-reduce, are used for the storage and computing of mass macro-economic data. Specially, MacroEconSim is developed using JADE (Java Agent DEvelopment framework) agent toolkits according to the FIPA (Foundation for Intelligent Physical Agents) specification, which makes the platform an open and inter-operational agent modeling and simulation environment. Meanwhile, MacroEconSim can provide standard function libraries for agent modeling, protocols for agent interactions, and high-level APIs for experiment design and data visualization.

We have so far built a large-scale population of artificial users in the platform, including tens of millions of economic entities, millions of enterprises and more than two hundreds of major economic institutions (for example, banks). The experiment scenarios include various kinds of important topics in macro-economics, such as the economic growth, inflation, international trade, monetary policy, energy economics, logistics scheduling, and so on.

6.2 A Case Study on Inflation

In this case study, the MacroEconSim experimental platform is used to conduct computational experiments for prediction, pre-warning and control decision of the economic inflation.

First, we can model various macro-economic participants, including banks, producers, consumers, investors and governments. Utility functions and risk functions are trained from real-world data for each kind of participants. Meanwhile, strategy sets are also provided. Besides, the monetary model, financial product (bonds, insurances and stocks) value models, futures (steel and oil) pricing models and goods production models are incorporated in the artificial macro-economic system, as is shown in Figure 4.

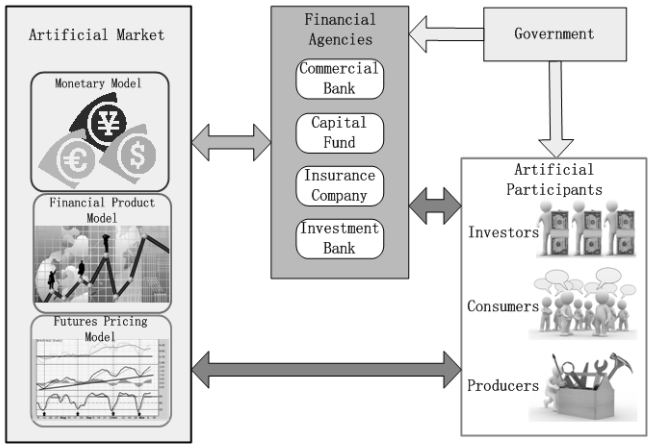

Fig. 4. The Artificial Macro-Economic Society

Second, based on evolutionary game theory, we conduct computational experiments on impacts of various environment parameters on the market inflation. Through representing and comparing result data, the evolution of various markets is observed and deeply analyzed. Besides, our approach also provides experimental evaluations for government control strategies such as adjusting the deposit reserve ratio, interest ratio and issuing bonds.

In the parallel execution, the MacroEconSim platform can update macroeconomic statistics and market transaction data (e.g., stocks and futures) using the data interfaces in real time. Sequentially, participant behavior models and environment parameters are modified in an online mode. Meanwhile, by computing and predicting the trend of market inflation, the platform supports early-warning for the macro-economic environment.

For illustrative purposes, we list a simulation algorithm based on evolutionary game-theoretic theory in our computational experiments with MacroEconSim.

ALGORITHM: Evolutionary game-theoretic algorithm for computational experiments on inflation

Inflation can be considered as the long-term stable outcome of the strategic interactions from co-evolving economic entities in the macro-economic systems. Therefore, we can use evolutionary game-theoretic simulation in the computational experiments on inflation [36, 37].

We first encode all possible strategies of the massive economic entities, such as government, financial institutions, enterprises and consumers, to strategy populations. Each strategy individual in the population denotes a kind of possible strategy. The strategy populations co-evolve to optimize their strategy individual and eventually converge to stable equilibrium strategies, which determine the degree of the inflation emerged in the macro-economic systems.

The detailed algorithm can be described as below.

***Input**: Strategy space of involved economic entities and their interaction mechanisms*
***Output**: Evolutionarily stable strategy of each entity*

Encode strategies of macro-economic participants;
Set the generation gen = 0;
while** (gen < MaxGeneration) **do
  gen = gen + 1;
  Select fittest strategies based on fitness;
  Evolve strategies by crossovers and mutations;
  Generate the offspring populations;
  Evaluate the fitness of offspring populations;
end while

***Sub-Algorithm**: Fitness Evaluation*
For each strategies to be evaluated, do
  Select a strategy from each other population;
  Do agent simulations with selected strategies;
  Evaluate the degree of inflation in simulation with quantitative indicators (such as CPI);
  Strategy fitness = the degree of inflation;
Return the fitness of evaluated strategies

We can use this algorithm to investigate the relationship between monetary policy and inflation rate based on the two-period overlapping generation (OLG) model [38, 39], in which the government can control the inflation dynamics by money supply, and individual entities (agents) aim at maximizing the product of their consumptions in two periods. As an illustrative example, we omit the detailed model description and parameter settings, and mainly present key insights derived from the computational experiments.

The detailed experimental result is shown below.

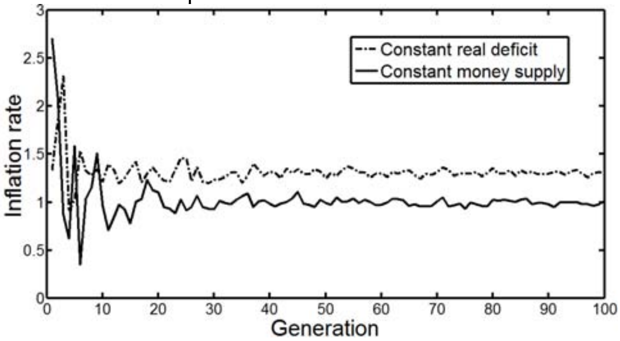

Fig. 5. Experimental Result of the Inflation Simulation.

We can see from Figure 5 that if the government keeps the money supply in each period constant, the inflation rate (measured by the ratio of the nominal price levels in the OLG model between two successive generations) will converge to 1, indicating that the price system will form a stable equilibrium without inflation. On the other hand, if the government uses a policy of financing the constant real deficit through seignorage, the OLG model converges to an equilibrium state with a positive inflation rate. The experimental results can help quantitatively explain and predict the inflation dynamics under specific monetary policies.

7 CONCLUDING REMARKS

With the continuously accelerating and popularizing of digital society, digital government and digital resources, the decision-makers, researchers and even the general public will be confronted with an increasingly large amount of socio-economic information in a dynamic and real-time fashion. Due to the rapid propagation of information, we must fully and effectively use the information in real time so as to improve the associated decisions. However, it's quite difficult to analyze and predict accurately these problems with inherent complexity. Therefore, it is important to study possible alternative versions of these problems, and the psychological effects on the performers, in order to make the corresponding decisions. As such, it becomes important and urgent to build the computational theory and methodological framework for complex socio-economic systems.

This paper is the first attempt to apply the computational theories and approaches in complex systems research to study the socio-economic issues. The basic idea is to systematically apply the artificial societies, computational experiments and parallel systems approaches into the quantitative, dynamic modeling and analysis of socio-economic systems, and in turn achieve the management and control on these systems. Currently, the ACP approach is still in its infancy, and there is still a long way ahead before its systemaltization, scientification and practicalization. However, we have enough reasons to believe and expect that the ACP approach can efficiently facilitate the development of socio-economic systems. Meanwhile, this research work also paves a new way for integrating and digitalizing diverse economic theories.

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