SYSTEM DYNAMICS STUDY ON COMPLEXITY

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Abstract **Since last century, complex systems, complexity problems and their research have become the basic problems of systems science, social-economic science, physics, biology and so on. Complexity science is so called the science of the 21st century. This paper looks back to the progress made on the study of complexity and complex systems in recent years and compares the Santa Fe approach with System Dynamics methodology in their dealing with complexity problems in social-economic systems. The latest outcomes of social-economic complex systems research, which were made by using the theory and method of System Dynamics, are also the focus of this paper. When System Dynamics came into being, it has faced a complex system of society, economy and ecology and already made important contributions to the study of social-economic systems. The key points of the study of System Dynamics are system structure and its relationship with corresponding behavior modes. Finally, the author proposes using System Dynamics as the basic approach and framework and synthesizing with other approaches to analyze and solve the problems of social-economic complex systems.**

This scheme is not only effective but also practical to complex social-economic-and eco-systems.

KEYWORDS: social-economic system system dynamics complexity

1. Introduction

The most important difference between Eastern philosophy and Western philosophy is that the former focuses on figuring out the characters and functions of entity in a holistic view, while the latter pays more attention to the analysis of the whole entity and has a good grasp of its traits and capabilities by researching its separate sections.

From the foundation of system science in 1930's to the development of complexity science research nowadays, the Western scientific community converts its focus from decomposing the whole into how the individuals constitute an organic system and how the system grows and evolves.

Cheng Siwei [1] holds the opinion that systems science has developed into a new stage, that is, complexity science. The concept of complexity science has its origins, which are the research discoveries and the new theories advanced in different specialized fields, such as cybernetics, Phase Transition theory (mainly studying the formation and evolution of equilibrium structures), Dissipative Structure theory (mainly studying the unbalanced Phase transition and self-organization), Mutation theory (mainly studying the discrete results aroused by continuous process), Synergetics theory (mainly studying the evolution and self-organization of systems), Chaos theory (mainly studying the internal stochastic phenomena of determinant systems) and Hyper-Cycling theory (mainly studying the self-organization on the basis of life evolvement).

Complexity is a common character, which consists in a great variety of systems (for instance, economic system, physical system and biological system). Although there are disagreements on the definitions of complexity and complex science, it is universally accepted that complexity will be the 21-century science.

At present, it is Santa Fe Institute (SFI) that is the most famous one in the research of complexity. It has put forward many new ideas and methods in the complex problems research field, and has carried on investigations in the specific social, economic and natural scientific problems, which have been given a wide attention.

Yet the theories, methods and tools of **System Dynamics (SD),** which was formulated by **System Dynamics Group, MITSloan** in mid 1950s and based considerable research achievements, could not be neglected in social economic systems research.

On the base of social economic systems' complexity study, the article compares the Santa Fe methodologies with SD methodologies, and provides the research methods framework of social economic systems problems.

2.The origin and development of complexity research

The complexity research originates from the complexity phenomenon and problem researches in each specific domain. For example, Ilya Prigogine, a chemical Nobel prize winner of 1977, whose main contribution is to bring forward Dissipative Structure Theory, discovered that a far-from-balanced-status system can realize self-organization process and thus keep a stable system by exchanging energy, materials and information with outside. Other examples are the Hyper-Cycling's research of the living system's evolved self-organization phenomena and the Organ Growth theory's research of the tissues' growing courses, etc. These problems are discovered and researched in a specialized subject. However, people gradually found that some phenomena are the commonness suitable to all the systems. For instance, the so-called "Butterfly effect", which was first observed in the atmospheric physics research, exists in the social economic system.

Based on the common characters, people gradually abstract the research problems and hope to find the corporate laws and methods that are effective to all the problems. The research to sort out the common rules behind different systems is factually the research of systems science. Therefore Cheng Siwei's assertion that complexity science is a new developing stage of systems science [1] is accurate.

It is accepted that social economic system is in possession of complexity traits. SD's initial research of social economic and ecological systems was in 1950s. Based on systems thinking, feedback theory and cybernetics, SD was founded in 1950s. It created social-economic-systems-objected SD models. Employing computer-based simulation, SD developed simulated and analyzed researches about the far-ranging problems of business systems, urban systems and national social economic systems, etc. For instance, the SD Group of MIT created "the World Model" for the famous **Club of Rome** and came into the conclusion of ***The limits to Growth.*** The American **System Dynamics National Model** (based on the non-equilibrium theory) successfully validated the **Western Economic Long Wave** in the economic system. And Peter Senge's SD-based theories played an important role in the fruit of **Learning Organization** researches. These researches are all accepted as the researches on the complexity or the complex systems [2 3].

It is the foundation of Santa Fe Institute in 1987 that indicated a new commencement of the complexity and complex system researches. In 1987 a group of prominent scholars, whose specialized fields vary from Physics, Economics, Biology to Computer Science, etc., came to the small city Santa Fe, which is not far away from Los Alamos, and established the Santa Fe Institute to take up the complexity researches specially. They attempt to find the uniform theories and methods to figure out the complex problems by cross-disciplinary communications and researches. The research springboard and methods of Santa Fe are in unique train of thoughts (the article will briefly present). [10] Through over twenty years' researches, the scholars of Santa Fe Institute have taken a lot of researches on the specific phenomena in diverse fields, and have published a series of papers. However the further researches of uniform theories and methods to solve the complex problems are in process.

It should be pointed out that though the thoughts and methods and the contributions of Santa Fe have given the complexity research **a new start**, **the complexity science is still in the initial stages as a whole**. The most convincing evidences are that there is no uniformly accepted definition of complexity at present, and complexity science has not come into an integrated theoretical system.

There are some other schools of complexity research in America, such as the structural foundation theory of George Mason University's Professor Warfield, whose main achievement is interactive management theory.

3.Comparison of the Study on Social-economic Systems by SFI and System Dynamics

3.1 Santa Fe Perspective and Approach to Social-economic Systems

SFI's view and methods about social-economic systems are called **Santa Fe Perspective and Approach** or Complexity Perspective and Approach. This is an observing method focusing on emergence and process. In the introduction of SFI's "Economy as a evolving, complex system", W. Brian Arthur advanced the basic perspective on social-economic systems: " social-economic systems are adaptive nonlinear network". And the main characteristics are:

(1). Dispersed Interaction: Economy phenomena are originated from the interaction of economic agents with different features. Any agent's activities rely on the prediction of other agents, and the whole state is made by all the agents.

(2). No global controller: no whole control effect. Control is made by the competition and cooperation between economic agents. Economic action is modulated by law systems and the duties granted. There are also no general competitors and any agent can develop all the opportunities in economy.

(3). Layer structure: Multi-layer organization structures exist in economic systems and there are interactions among these layers. Units in any layer have behavior, action, strategy and output and they are the basic components of the higher layer. The whole economic system is stratified and interactions are among different layers.

(4). Continuous adaptation: The whole system is continuously adaptive with the accumulation of experience and the modulation of agent's behavior, action, strategy and output.

(5). New things in economy: New economic prospects can be made by new markets, new technology, new action and new systems.

(6). Dynamic state far from equilibrium: The new things, new potential and new opportunities emerging in the economy, the real economy often operates far from the optimal or equilibrium state.

In conclusion, it can be posited that SFI views the social-economic system as a dynamic, continuously evolving system far from equilibrium. This social-economic system is made up of agents which have intelligent behavior of predicting and learning so that the economic system has a mechanism of self-adaptive. Restrained by certain system and laws, many agents make the economic system develop to an advanced structure, form complex layer-structure and keep on evolving through limited interactions. These perspectives are different from the mainstream classic economics based on the equilibrium thought and the dynamic economics based on the optimal control. Santa Fe's thoughts on social-economic systems represent its criticism on the already-existed economy theories and its exploration of new economy theories. But till now these perspectives haven't formed a complete theory system and can't replace the already-existed economics theory.

Santa Fe Approaches are based on its perspectives on the social-economic problems. It uses many mathematics methods and random process and carries on computer simulation. In fact, Santa Fe Approaches come from computer simulations. A typical calculating procedure is as follows: firstly, separate the systems under research into a lot of different agents and define every agent and the way it affects other agents. Secondly, define the rules and restrains in interactions. Then, put these agents into certain circumstances to carry on random interactions and these interactions totally simulate real economic units' interactions, so it can be regarded as the simulation of the real economic systems' developing and evolving. Finally, after long-time computer simulation, social-economic structure and general characteristics can be analyzed.

Santa Fe Approach has its special way of thinking and its key point is to show the evolving procedure of social-economic systems by economy units' effect on computers. This approach is in the state of development and lacks complete theory systems, generalized methods and simulating software implements. Facing the huge and complex social-economic systems, this approach is sometimes incapable.

Although the complexity study of Santa Fe has advanced thoughts and has made achievements, this study is just a beginning and the gate of complexity science is still not thoroughly opened to the dedicated and wise people.

3.2 System Dynamics Perspective and Approach on Social Economic System

System Dynamics (SD) is a theory and methodology of studying social, economic and ecological system. Basic knowledge on social and economic system, which the approach needed mainly, relies on the existing social and economic theories.

From the point of view of Systems Science, System Dynamics considers the social and economic system as a high order, multi-feedback loops and non-linear complex system with some dominant feedback loops. The behavior of such system holds counter-intuitive characteristics and is insensitive to the change of most parameters in the non-dominant loops in the system.

The principal idea of SD is that the interior structure and its change of system determine the function and behavior of a system. It shows behavior of the social and economic systems by establishing computer simulation models which capture system structures.

In recognizing the system structure and modeling, SD takes a quite different method from Santa Fe's. SD analyzes the system structure and feedback ways before modeling. A system is divided into several sub-systems whose main variables are defined. Among these, the **state and rate** variables are identified from generic structures. After quantitative relations are determined among the variables, SD model is established. The analysis of structure in System Dynamics pays more attention to the analysis of feedback loops, dominant loops and structures, information flows material flows, etc.

The theoretical foundations of SD are the feedback theory, control theory, information theory, non-linear theory and large system theory, etc. SD model is by nature equivalent to a series of non-linear differential equations.

System Dynamics has standard and normal methods for modeling, e.g. to establish the complicated non-linear relationship among variables with corresponding functions or table functions and to describe actual delay relation with delay functions of material and information.

System Dynamics has its professional computer simulation softwares, which have experienced several generations of development and are very practical, to support modeling and simulation.

Within its nearly 50-year development, SD has been extensively applied in the complex social and economic systems. For instance, in early 1970s the Club of Rome and MIT Sloan used SD World Model to explore the problems of world development and put forward that world development will be restricted by resources and environment, which brought universal concern to resource and environment problems. And the Urban Dynamics models and National Model of the MITSloan are other examples. Another most important application of SD is in the business management, which is originated in 1956. Learning organization is also based on the research of organization in System Dynamics.

It can be seen that from the perspective of solving the actual problems in the complex social and economic system, System Dynamics is mature in the theoretical methods and tools. But it needs further research as to study the emergence of new structures. Whereas, in this field Santa Fe approach has been able to simulate the emergence of new structures by researching the evolution on the basis of individual mutual influence.

4. Recent Research on Social-economic Complexity Systems by System Dynamics

4.1 Brief Survey on the System Dynamics Models of Two-Sector Economy

The methods of system dynamics can be used to study the complexity of social economic systems. The following is the analysis of the two-sector social economic system by the use of system dynamics.

It has been proved that a turnpike exists in the economic growth of linear multi-sector economy. But this turnpike is usually not steady, which is a real economic problem in our study. There are two parts in the industrial composition of economic systems. One grows rapidly and we call this part new industry; the other grows slowly and can be viewed as traditional industry. These two industries rely on each other. So we set up a system dynamics model with an exogenous technology progress, based on Walras general equilibrium, nonlinear and growing in new classic two-sector economy.

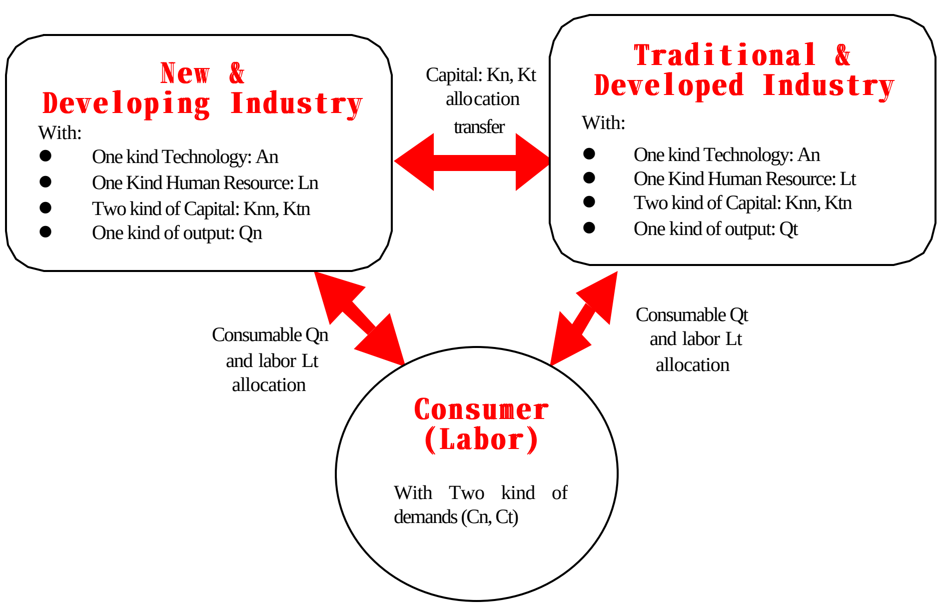

Figure 1. The two-industry model

Note: The action and reaction of two industries follow: Two kinds of capital, two kinds of consumable, and two kinds labors are allocated to two industry based on walrus general equilibrium.

In Figure 1, you can find the whole economic system is divided into 3 part. The two key sectors are the new & Developing Industry, and the Traditional & Developed Industry. Figure 1 gives the description of the mutual action and resource allocation between two sectors.

The system dynamics model we set up is as Figure 2.

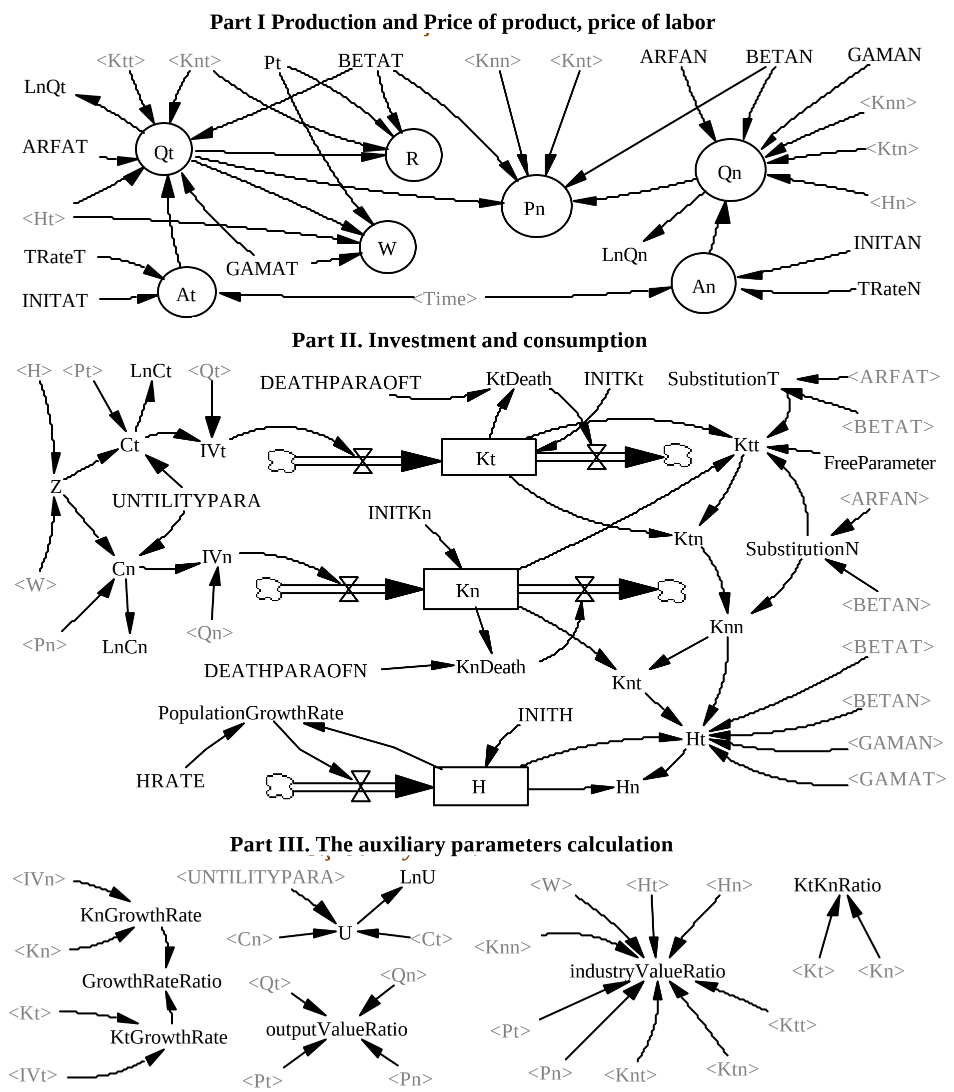

Figure 2. The two-industry economic evolution and growth model based on Warlas General

Through simulated test, the main outcomes of simulation are showed by the following figures. As the figure shows, initial capital Kt0 is hypothesized as a constant and initial capital Kn0 is changed. We can see that the subtle differences of Kn0 can lead to the change and deviation of large capital ratios and form a divergence around the central curve.

Table 1 Simulation Parameters

Runs	**TEST1**	**TEST2**	**TEST3**	**TEST4**	**TEST5**	**TEST6**
Kn0	617.507	617.506	617.5	617.514	617	618
Terminated time	46	45	37	41	25	30

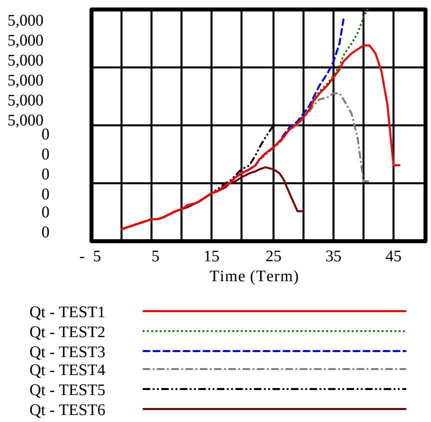

Figure 3 The bifurcation of Qt's trajectories

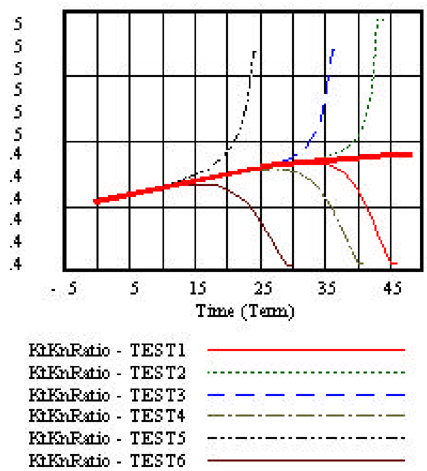

Fig 4 bifurcation and turnpike

It can be seen that this model is set up according to the relation and impact between new industry and traditional industry in economic growth. The model is strictly based on the general equilibrium of Walras, which makes capital, labor force, other resources, commodity price, salary and capital interest certain. So every step of economic growth is in equilibrium state and economic growth is the extension of every temporary equilibrium. The two major conclusions are:

The simulation proves that the economic system is very sensitive to initial capital structure. The tiny variation of capital ratio will bring great deviation to economic growth path; the nonlinear bifurcation appears. However, there exists a mid-trajectory in all bifurcation paths of one variable. While economic system runs along with this mid-path, economic evolution will last longer times, so it is the optimal evolution path. We express this path with thickline in Figure 4. In fact, it can be regarded as the economic growth turnpike in this nonlinear model.

In real economic system, because of great difference of initial resource gifts, Kn/Kt will vary greatly. Further more, there are many disturbances in economic system, so it is impossible to keep Kn/Kt constant or in a small range of variation, therefore, the two-sector economic system based on general equilibrium must be unstable.

4.2 Study on the National Model by System Dynamics

4.2.1The whole structure of the model

There are six main sub-sectors in American SD National Model. To simplify the model, they can be combined to three bigger sectors (Figure 5).

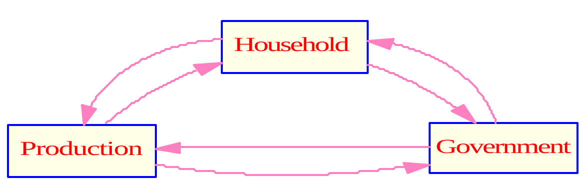

Figure 5. The Assumption of A Simplified National Model

There is complicated information and material exchanges among 3 sectors. However, to make the beginning easy, we put focus on production and make light of the effect of government temporarily. The effect of government can be replaced by some exogenous variables temporarily, so we merely need to analyze the relations between the two sectors.

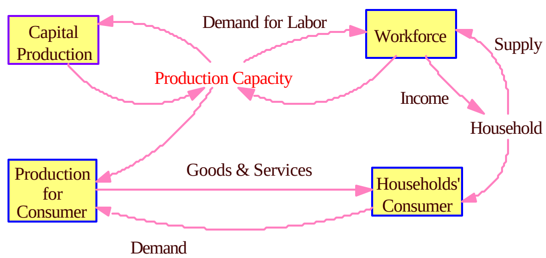

Figure 6 Simplified National Model

From Figure 6 the core of the model which lies in production sector can be found out. In order to reduce the complexity of the model, we think much of the society production sector. So some simplification is made to the family sector. First, assuming that the supply of the labor force is sufficient, the demand of the labor that is mainly determined by production capacity is discussed. Second, family income is the primary element that affects consumption. And the price of labor force providing by family is exogenous, not determined by labor market. Third, production capacity is determined by production function.

The effect of the government involves two aspects ----government and finance, which are substituted by 3 exogenous variables to simplify the model. They are investment of permanent assets from statistical almanac, government consumption and interest rate of resident savings. Of course, price index is also regarded as exogenous variable and only work in the field of consumption.

There are 11 levels in the model totally. Four of them are smooth functions, and others are capital levels in the production of capital goods, consumable stock in the production of consumables, labor at work from families and family saving, etc. In addition, there are 11 rate variables in the model, in which increase of capital goods per year, depreciation of capital goods per year, increase of consumables per year, production rate, hire rate, family income and family consumption per year are the most important. Other rate variables are mostly order rates. Furthermore, in the model there are more than 100 equations, which involve some parameters and table functions as constants. They'll be discussed specially in the following part. To sum up, the model is a small one and easy to adjust and run.

4.2.2 Results of Simulation

To build up the model, the latest SD software----Vensim is used . The length of the simulation is 45 years, from 1952 to 1996. Once fixing the initial values and inputting the exogenous variables, the model can be run after some slight adjustment. The initial value of the labor is 207290 thousand persons. The initial value of the productivity is 55000 million RMB (according to the price of that year). The initial order of the consumables is 37500 million RMB. The following is the result:

(1) In Figure 7 you can see 2 curves about GDP. Curve1 (TGDP) stands for the GDP from statistical almanac; curve 2 (GDP) is the result of simulation. The unit is RMB/year. Obviously, the difference between them is very small relatively, and they are consistent in the developing trend, which is just we expected.

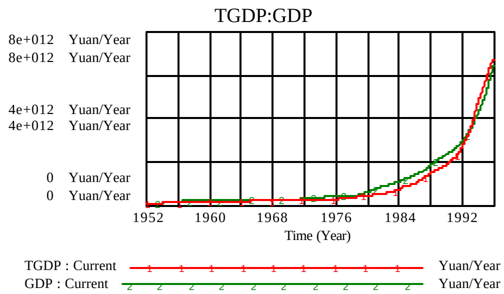

Figure 7. TGDP and GDP

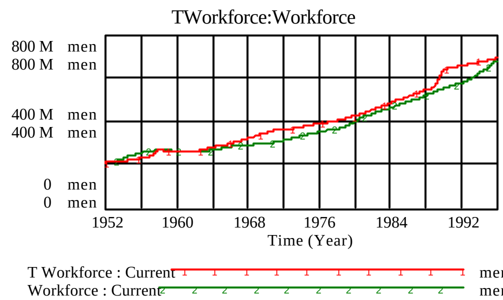

Figure 8. Tworkforce and workforce

(2). In Figure 8 you can see 2 curves about labor. Curve 1 (Tworkforce) stands for the labor from statistical almanac; curve 2 (Workforce) is the result of simulation. The unit is person. As you can see from the figure, the two curves have difference in some periods, but they are uniform in developing trend, which can meet the requirement already.

(3). In Figure 9 you can see 2 curves about the output per capita. Curve1 (TWOR) stands for the data from statistical almanac; curve 2 (WOR) is the result of simulation. The unit is RMB/person year. From the figure we can see the two curves have apparent difference in two phases. From 1955 to 1993 the result of simulation is higher than actual data, which is caused by recessive unemployment (that is to say, actual labor is lower than the data from statistical almanac), because the simulation result of GDP is higher than the data from almanac that phase. The other phase is from 1993 to 1996, when simulation result is lower than statistical data. The reason can be found from the difference of labor. Nevertheless, the simulation result is still reliable. At least, their trends of development are consistent in the past 45 years.

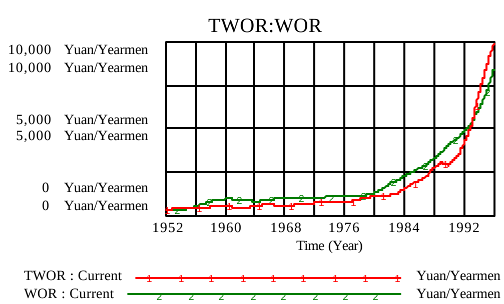

Figure 9.

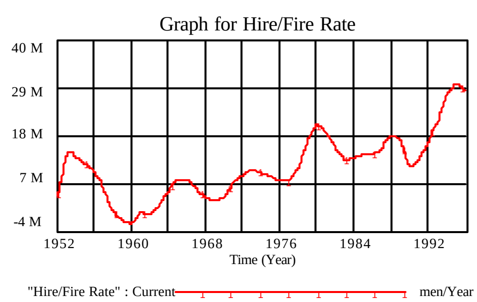

Figure 10

Of course, we can offer curves about more variables, such as family saving.

4.2.3Analysis with instances and an interesting conclusion

In the foregoing part, the result of simulation has been described. In fact, by analyzing the result we can make some academic discussion on the situations of our economy in the past 50 years. Take Hire/Fire Rate for example (Figure 9).

The equations related to H/F Rate are as following:

Hire/Fire Rate = (desired labor - labor level)/ Adjustment Time of labor

Desired labor = desired production capacity / average productivity

Therefore, desired production capacity is determined by output per year and a correlative fraction (IPD Fraction):

IPD Fraction = (consumption per year + capital depreciation per year + change of consumable stock) / output rate per year

4.2.4 Summary

According to the result of simulation, we have reached the goal to create the model. Then, what other functions does the model have? It has 3 kinds of function at least.

First, as we have discussed, it can be used to study the economy cycle and the cause of its formation.

Second, it can be used to study economy long wave, for example, whether there is long wave in the operation of our economy, and how it will affect our economy. More discussion about the issue will be presented after further study.

Third, after the model is improved, that is to say, all the exogenous variables become endogenous, we can make some policy analysis and forecast development trend. The most important is to study the long-term development and the effect of long wave on other economy factors, which is our ultimate goal to create the model, and our goal to strive as well.

5. The method frame of System Dynamics on the research of complex social and economic system

It can be seen from the two cases above that System Dynamics can surely be applied in the research of the complex social and economic system. However, System Dynamics also need development in face of the development of Complexity Science. Hence, the author put forward the frame for studying the complex problems as follows:

(1) With the beginning of the problems to be solved, to give the target system a profound **systems thinking**.

Every modeling is for solving the existing concrete problems, thus it's unnecessary and impossible to make models completely correspond to the real world. Real systems should be abstracted and simplified in the analysis of the target system, to which System Dynamics usually pay much attention.

And then Santa Fe approach can be used as reference to analyze the possible evolution model of the system. Further analysis of the feedback and its consequence can be made; diagram of feedback loops can be set up and states and rate variables can be identified.

(2) Establish models mainly with System Dynamics, yet integrated by many other approaches.

For instance, in establishment of the SD equations, econometrics approach can be used to determine some relative parameters. To establish the relationship among the layers of the system, **AHP** analysis approach can be used.

In addition, some new SD simulation software (e.g. Vensim For DSS) can transfer external functions and sub-systems, which provides interfaces for System Dynamics to other simulation approaches. Thus, some complex sub-system can be modeled by non-SD approaches (e.g. Santa Fe type) and can be combined with SD models through transfering with DSS.

(3) Conduct the simulation experiment of the models.

Specific simulation calculation should be conducted and validation test should be made to the simulation results, during which parameters should be adjusted until the requirements of the validation test are met. Meanwhile, validating analysis and test also should be carried out to other transferred models.

The comprehensive model created based on System Dynamics is **a simulation lab** of the real social and economic system. Hence, in the simulation, kinds of strategy and policy analysis can be made.

(4) Analyze the simulation results and achieve meaningful social and economic conclusions.

Data from the simulation analysis based on the model have to be endowed with social and economic meanings. The simulation results should be analyzed, compared and considered in detail in order for the achievement of the meaningful social and economic conclusions.

In all, the basic frame of this approach and the iterative process are: beginning with the systems thinking of the problem together with the quantitative and qualitative analysis, and mainly basing on System Dynamics Modeling combined with other approaches to establish the comprehensive model which could be simulated and analyzed by computer. And after the validation test and comparison with the real social and economic system, meaningful social and economic conclusions might be achieved and the problems might be solved.

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