The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making

Long, Q. and Li, Shuliang

https://dx.doi.org/10.1109/ISDEA.2014.234

Long, Qingqi and Li, Shuliang (2014). The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making. In: Proceedings of the fifth international conference on intelligent systems design and engineering applications (ISDEA 2014) 15th-16th June 2014, Zhangjiajie, China. IEEE-CPS, pp. 1060-1064. ISBN 9781479942619

The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making

Qingqi Long [1], Shuliang Li [2,3]

[1] School of Information, Zhejiang University of Finance & Economics, Hangzhou, Zhejiang, 310018, China
longqingqi1116@163.com
[2] Westminster Business School, University of Westminster, London, NW1 5LS, United Kingdom
lish@westminster.ac.uk
[3] School of Economics & Management, Southwest Jiaotong University, Chengdu, Sichuan, 610031, China
simonxnjd@gmail.com

***Abstract* — The literature rarely considers an innovation network as a complex adaptive system. In this paper, theories of complex adaptive systems research are employed to model and analyze intra-organization networks, inter-organization networks as well as their interaction mechanisms in the whole innovation context, with a conceptual framework proposed and presented. Flexible multi-agent based modeling, smart simulation, self-survival and adaptive intelligent software agents, expert systems, analytic hierarchy process, hybrid decision support approach, and statistical methods are integrated to deal with the innovation network problem and support evolutionary decision making in the open and dynamic environments.**

Keywords - Innovation network; complex adaptive system; multi-agent based modeling; simulation; evolutionary innovation decision making; hybrid decision support system

I. INTRODUCTION

Product and service innovation is pivotal to any enterprises and even any countries. Environmental complexity, fast changing customer requirements, strategic shifts of competitors, cooperation changes of partners, and even upgrades of technologies all bring significant challenges to innovation and associated decision making. Enterprises are no longer isolated, but connect and interweave with external environments and form complicated networks, where information and ideas are exchanged quite frequently. Businesses not only pay attention to product research and development, but also make choices amongst innovation, imitation and process improvement [1]. The inter-organization network is vitally important [2].

An innovation network is a typical complex adaptive system (CAS) [1]. It evolves with time and space. Uncertainties, stochastic factors, interactions, self-organization, emergence and development are the main characteristics. Customers, communities, markets, competitors, collaborators and suppliers, heterogeneously located in the network, are dynamical subjects which interact with each other, conduct self-reasoning and make self-decisions. Limited information, knowledge and ideas may make enterprises' decision-making process more subjective. Moreover, uncontrollable factors and unexpected events increase the complexity of innovation network evolution.

Holland, an American computer scientist, first proposed the concept of complex adaptive systems [16]. Its principle is that subjects in a system can continuously interact with other subjects and environments, learn and accumulate experience in interaction processes, and by the experience, modify and adjust their own structure and behavior. In this way, new structure, phenomena and more complex behavior in the macro level may be emerged. The complexity of complex adaptive system stems from the subjects' adaptabilities. It means the adaptability produces complexity, named as CAS theory. The theory emphasizes micro subject modeling and considers macro phenomena and behavior evolving from subjects' interactions. This theory would fit the nature of systems' evolution and has been widely used in many research fields such as ecology, physics, military, society, and management. Nonetheless, only quite recently, the innovation networks are considered as complex adaptive systems by some researchers and scholars [4, 5].

Multiple intelligent agents-based simulation enables flexible "what-if" analysis and can help explore the various scenarios and possible consequences and identify where to improve before taking any innovation stakes. Multi-agent based modeling is a powerful approach to complex systems research and has its own strengths [6, 7, 8]. It is different from game theory and system dynamics, which simplify complex systems and treat complex issues as simple ones. The multi-agent based method, integrating with other systems modeling and decision support techniques, allows modelers to model complex systems in a flexible, intelligent, intuitive and straightforward manner. Only micro agents composing a complex system and its interactions need to be specified and represented. The higher macro level of phenomena emerges as a result of agents' interactions, communication, cooperation and negotiation. Therefore, intelligent multi-agent modeling is particularly suitable for the research of such complex systems as innovation networks. In addition, innovation networks and multi-agent systems share many similar essential features [9].

Long, Qingqi and Li, Shuliang (2014). The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making. In: Proceedings of the fifth international conference on intelligent systems design and engineering applications (ISDEA 2014) 15th-16th June 2014, Zhangjiajie, China. IEEE-CPS, pp. 1060-1064. ISBN 9781479942619

Nevertheless, the use of multiple intelligent agents in innovation networks has not gained enough attention and relevant work is still in its infancy [1].

This paper treats the innovation network as a complex adaptive system and proposes a flexible multi-agent based modeling, smart simulation and decision analysis framework for evolutionary innovation in a dynamic context.

II. THEORETICAL FOUNDATIONS

A. *Complex innovation networks*

Innovation networks integrate multiple adaptive subjects which are connected together with ideas and information flowing in and out to help make innovation decisions. Generally speaking, the innovation network of a certain enterprise is composed of an intra-organization network and inter-organization network. Decision making for product and service innovation always depends on the intra-organization network. In fact, an enterprise is normally consists of multiple departments, such as production department, marketing department, financial department and R&D department. These departments connect, communicate and interact with each other, and are coordinated by senior management. Taking into account the impacts of the inter-organization network on decision making processes, it is essential for the enterprise to connect and interact with such external subjects as customers, competitors, partners, suppliers and mainstream technologies. It is argued that the innovation process should incorporate internal and external ideas, information and knowledge involving spinning-in and spinning-out activities [10, 11, 12]. We propose a diagram in figure 1 to illustrate an innovation network of an enterprise. The rectangle is the enterprise's boundary. The enterprise needs to devise and adjust its product and service innovation strategies in order to respond to external environments and thus to achieve sustainable competitive advantage. Therefore, decision making processes can be functioned as the results of interactions and idea exchanges across its intra-organization network and inter-organization network.

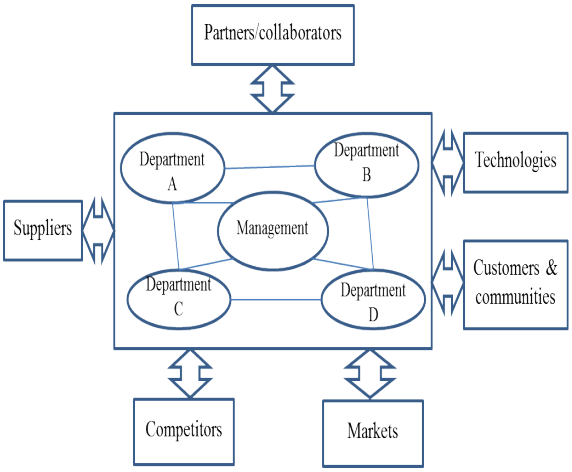

Figure 1. An innovation network as a complex adaptive system

As shown in figure 1, the adaptive subjects or players in the innovation network are not completely rational. Business information protection and idea blockage are quite common. The innovation decision making process is always complex and full of randomness, uncertainty and even politics. Furthermore, decision makers are faced by a number of favorable and unfavorable factors in relation to customers' demands, market trends, competitors' strategies, partners' cooperation issues, suppliers' promises, and technology development. In the long period, the evolution of innovation networks has a strong nonlinearity and irreversibility. Thus, it is necessary to deal with the innovation network as a complex system and investigate the use of effective methods, techniques and tools as a good solution.

B. *Flexible multi-agent based modelling, smart simulation and intelligent analysis*

Multi-agent based modeling and simulation has salient features such as flexibility, hierarchy and scalability. Flexible multi-agent based modeling and simulation enables the linkage and combination of the micro behavior of individuals and the macro level of emergence of the whole system together. It has been proven an effective modeling solution for coping with issues related to complex systems. Following a bottom-up modeling approach, autonomous and interactive agents are created to model individuals and their micro behavior in a complex and changing context. The agents' social abilities to character individuals' interactions are utilized to build multi-agent simulation models. While these models can be implemented in a single simulation platform, the systems' emergence can be visually observed. Outputs and results can be collected for in-depth analysis.

The characteristics of the subjects composing an innovation network are somewhat similar to the features of software agents in terms of intelligence, reasoning, autonomy or relative independence, negotiation, communication and interaction. An innovation network is also distributed in nature. Therefore, multi-agent systems can be designed and programmed to implement distributed computation of innovation networks in dynamically changing environments. Agents and aggregate agents can be developed to describe and represent subjects and their interactions. And the complex behavior of innovation networks can be studied and explored through intelligent agent simulation and analysis.

The procedure of multi-agent based modeling and simulation can be divided into two phases. At the first phase, the main activities include agent-based innovation network structure creation, agents' behavior and rules modeling, and agents' interaction specifications. The latter phase includes activities of simulation model implementation, simulation environment configuration, run time definition, simulation run or execution, data collection and analysis.

Long, Qingqi and Li, Shuliang (2014). The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making. In: Proceedings of the fifth international conference on intelligent systems design and engineering applications (ISDEA 2014) 15th-16th June 2014, Zhangjiajie, China. IEEE-CPS, pp. 1060-1064. ISBN 9781479942619

C. *Innovation decision making*

It has never been an easy task for managers to make a decision on product or service innovation due to the complexity of the problem itself. In addition to the use of multi-agent modeling and simulation, other artificial intelligence and decision support approaches and techniques, such as expert systems (ESs), decision support systems (DSSs), analytic hierarchy process (AHP) [20], fuzzy logic [18, 19], Web analytics tools, and statistical methods can certainly be applied to support innovation decision making and strategy formulation.

III. CONCEPTUAL FRAMEWORK

A. *Multi-agent based modeling for innovation networks*

1) *Creating agent-based innovation network structure*

The first step in the modeling process is to create agent-based innovation network structure or architecture. In figure 2, we propose an agent-based innovation network structure containing multiple agents on the basis of figure 1. In order to analyze the enterprise's internal decision making process, the whole enterprise can be divided into multiple departments, which can be defined as production department agent, marketing department agent, financial department agent and R&D department agent, and senior management agent. The innovation decisions emerge as result of these agents' interactions. In real-world situations, the types and numbers of department agents are determined by actual decision making process of the modeled business. The inter-organization network has significant impacts on enterprise's internal decision making. In this architecture, the inter-organization elements include market agents, supplier agents, competitor agents, partner agents, customer & community agents, decision support agents, web information (social media and Web analytics, etc.) agents and technology monitoring agents. Although technologies and web information are not active subjects, they play a very important role in evolutionary decision making for product and service innovation. For this reason, these two types of agents are modeled as active agents. Besides, customer agents and web information agents are designed as monitors respectively and are responsible for searching for, collecting, filtering and analyzing information from customers and Word Wide Web, and social media, in particular. Decision support agents are also active, and are designed to assist managers in choosing a course of action for innovation through utilizing various sources of data, ideas, decision making models and artificial intelligence techniques and technologies. In order to solve conflicts among internal and external software agents, a coordination agent is provided.

2) *Modeling agents' behavior and rules*

Agents' behavior and rules determine how agents to act and interact to create system's macro emergence. Since the system's status changes are driven or triggered by events in an innovation network, the agents are defined in this paper as reactive agents that select and execute appropriate behavior responding to the coming external events. Before representing agents' behavior and rules, a unified formal definition for agents is as follows:

$$Agent ::= < Time, Message_{in}, Message_{out}, Status, IA, OA, B, R >$$

"$Time$"stands for simulation time and each of the agents uses it for time synchronization during the simulation execution, for the reason that agent-based innovation networks are distributed systems. $Message_{in}$ and $Message_{out}$ are defined respectively as the set of input messages from other agents and the set of output messages to other agents. "*Status*" is the set of agent status. IA represents the agent group where the input messages come from, while OA represents the agent group where the output messages are sent to. B is related to the behavior of each agent defined in advance. R is the evolutionary rules for each agent.

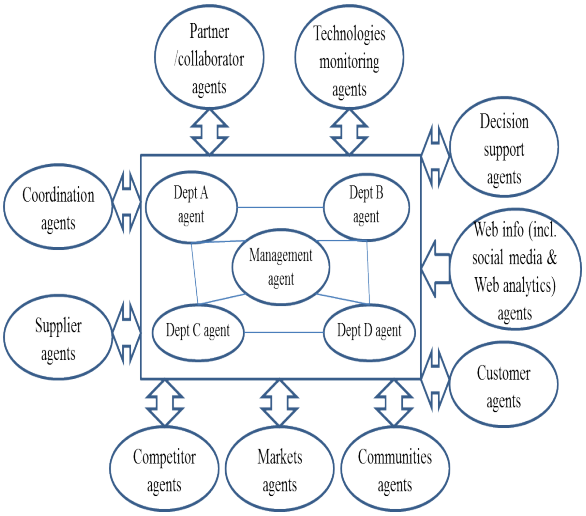

Figure 2. Multi-agent based architecture for innovation networks

In order to analyze complex behavior in enterprises' decision making processes without losing the complex nature of innovation networks, behavior and rules of external agents are defined as follows:

Customer and community agents generate stochastic product or service demands, ideas and preferences with uncertain quantities and times.

Competitor agents make their decisions on their innovation, imitation and other action with certain probabilities.

Partner agents stochastically change their cooperation depth and intensity with the modeled enterprise.

Supplier agents provide parts and materials and may be out of stock with certain possibilities.

Market agents monitor and report market trends, market changes and economic climate.

Web information agents monitor and collect product and

Long, Qingqi and Li, Shuliang (2014). The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making. In: Proceedings of the fifth international conference on intelligent systems design and engineering applications (ISDEA 2014) 15th-16th June 2014, Zhangjiajie, China. IEEE-CPS, pp. 1060-1064. ISBN 9781479942619

service evaluation, comments, feedback, ideas from social media.

Technologies monitor agent upgrades the technologies with a certain speed.

Decision support agents monitor decision making request and deliver tailor-made support for innovation strategy formulation and decision making.

The internal department agents' behavior and rules are defined according to the following specifications.

(1). Each department seeks maximum benefits in line with its revenue or customer satisfaction goals.

(2). A certain effort for cooperation exits across departments under coordination.

The tasks of the coordination agent are to maintain and monitor agents' interactions; to coordinate internal agents and external agents; and to resolve conflicts or disagreement amongst department agents using conflict resolution mechanism.

3) Agents' interactions

Innovation strategies emerge along with agents' interactions. Agent interaction is based on message exchanges. The information of events is carried by messages interchanged between agents. Each agent has two basic components, namely message parser and event processor. Its message parser will select the first message from its receiving message queue and analyze the message type and corresponding event lists, an then deliver them to event processor to perform appropriate behavior. All messages that the agent creates will be pressed into its sending message queue according to the timestamps and will be sent to the external agents by the "SendMessage" method. In this study, FIPA-ACL language is used as the standard for agent interactions.

B. Multi-agent based simulation for innovation networks

1) Implementing the agent-based model of innovation networks

This step is to realize and implement the agent-based model of innovation networks on the simulation platform. The agent-based model is translated into agent-based software programs. There are different agent-based simulation platforms, for example, Netlogo and JADE, which support the implementation of agent-based models through graphical user interfaces.

2) Configuring the simulation environment of innovation networks

Enterprises' boundaries should be specified in simulation environment configuration. An innovation network consists of multiple enterprises. Each of them has its boundary and is heterogeneously distributed in the network. The internal departments also have their own boundaries. Therefore, a distributed and heterogeneous simulation environment is configured to support the simulation of the actual environments of innovation networks. All agents located in the environments connect each other by network communications.

3) Determining run time

It is necessary to determine a suitable run time with better insights into the operation processes of innovation networks. The two parts of run time are: simulation repetitions and the length of each simulation. Due to stochastic and uncertain factors in simulation runs, adequate numbers of repetitions are required to obtain more stable, steady and valuable simulation outputs. At the same time, a suitable length of each simulation is also necessary for the users to obtain overall insights into the whole operation of the simulated innovation process.

4) Running the simulation model

After having finished the steps discussed in the previous sections, multi-agent based simulation model executes and runs according to the pre-determined run time and settings.

5) Collecting simulation data

This step is to gather the simulation results and store them in Excel files or databases for follow-up statistical analysis.

C. Decision support for innovation

We propose a hybrid decision support method [13, 14, 15, 17] for innovation. The strengths or powers of individual artificial intelligence and decision support techniques, technologies and approaches are utilized to match and deal with the various facets and properties of the innovation decision making problem. Fuzzy logic [18, 19] can be embedded into intelligent agents to tackle uncertainty and ambiguity issues in various factors. An ES can be developed to capture innovation knowledge and advise innovation strategies and alternatives. AHP [20] can be applied to compare and evaluate relative importance or priorities for different innovation alternatives against certain criteria in a hierarchical structure. Multi-agent based simulation can be employed to perform "what – if" analysis for innovation scenarios. This simulation process can be enhanced by dynamic graphical displays and animation movies. Intelligent self-survival and adaptive software agents can be created to stimulate idea generation and support evolutionary decision making for innovation.

IV. CONCLUSIONS

This paper has been sought to model and analyze the innovation network as a complex adaptive system in the open and dynamic environments. The innovation network structure, flexible multi-agent based modeling and simulation framework, and associated hybrid decision support approach are proposed and discussed in the paper.

Research work on creating and validating a multi-agent software system on the basis of the proposed framework is being undertaken. Case studies on multi-agent enabled evolutionary decision making for innovation networks will also be a priority for the next stage of this project.

ACKNOWLEDGEMENTS

This work was supported by Zhejiang Provincial Natural Science Foundation of China (Number: LQ13G010003), Zhejiang Philosophy and Social Science Planning Project of

Long, Qingqi and Li, Shuliang (2014). The innovation network as a complex adaptive system: flexible multi-agent based modeling, simulation and evolutionary decision making. In: Proceedings of the fifth international conference on intelligent systems design and engineering applications (ISDEA 2014) 15th-16th June 2014, Zhangjiajie, China. IEEE-CPS, pp. 1060-1064. ISBN 9781479942619

China (Number: 13NDJC039YB), Sichuan 100-Talent Scheme (bai ren ji hua, China), the University of Westminster staff research allowances (UK), the grants from National Natural Science Foundation of China (Grant numbers: 71090402) and the Major Program of the National Natural Science Foundation of China (Number: 71090402). The publication of this paper is funded by Sichuan 100-Talent Scheme research grant (Grant holder: Shuliang Li), P. R. China and the University of Westminster staff research allowances (UK).

REFERENCES

[1] R. Garcia. Uses of agent-based modelling in innovation/new product development research. Journal of Product Innovation Management, 2005, 22(5): 380-398.

[2] A. Karna, F. Taube, & P. Sonderegger. Evolution of innovation networks across geographical and organizational boundaries: A study of R&D subsidiaries in the Bangalore IT cluster. European Management Review, 2013, 10(4): 211-226.

[3] J. Holland, Hidden order: How adaptation builds complexity. Cambridge, MA: Perseus Books, 1995.

[4] Y.A. Zhang & C. G. Li. CAS simulation on network structure influences innovation resource utilization in innovation network. In: EBISS proceedings of the 2nd International Conference on E-Business and Information System Security, 2010, pp. 218-222.

[5] L. Klerkx, N. Aarts & C. Leeuwis. Adaptive management in agricultural innovation systems: The interactions between innovation networks and their environment. Agriculture Systems, 2010, 103(6): 390-400.

[6] A. Adetola, S. Li, A. Rieple & T. Níguez. Linking social media, intelligent agents and expert systems for formulating open innovation strategies for software development. In: WSEAS proceedings of the 11th International Conference on E-Activities, 2013. pp. 234-240.

[7] Q. Q. Long, S. Li & A. Hopgood. A multi-agent-based novel framework for flexible and tailorable modelling and smart simulation for supply chains. In: WSEAS proceedings of the 11th International Conference on E-Activities, 2013, pp. 59-63.

[8] Q. Q. Long, J. Lin & Z. X. Sun. Modeling and distributed simulation of supply chain with a multi-agent platform. International Journal of Advanced Manufacturing Technology, 2011, 55(9-12): 1241-1252.

[9] O. Labarthe, B. Espinasse, A. Ferrarini & B. Montreuil. Toward a methodological framework for agent-based modelling and simulation of supply chains in a mass customization context. Simulation Modelling Practice and Theory, 2007, 15(2): 113-136.

[10] H. Chesbrough. The era of open innovation. Sloan Management Review, 44: 35-41.

[11] O. Poot, D. Faems & W. Vanhaverbeke. Toward a dynamic perspective on open innovation: A longitudinal assessment of the adoption of internal and external innovation strategies in the Netherlands. International Journal of Innovation Management, 2009, 13(2): 1-24.

[12] J. Penin, C. Hussler & T. Burger-Helmchen. New shapes and new stakes: a portrait of open innovation as a promising phenomenon. Journal of Innovation Economics, 2011, 1(7): 11-29.

[13] S. Li. The development of a hybrid intelligent system for developing marketing strategy. Decision Support Systems, 2000, 27 (4): 395-409.

[14] S. Li & J. Z. Li. A multi-agent based hybrid intelligent framework for international marketing planning under uncertainty. Intelligent Systems in Accounting, Finance & Management, 2009, 16(3): 231-254.

[15] S. Li & J. Z. Li. WebInternational: combining Web knowledge automation, fuzzy rules and online databases for international marketing planning. Expert Systems with Applications, 2010, 37(10): 7094-7100.

[16] J. H. Holland. Studying complex adaptive systems. Journal of Systems Science and Complexity, 2006, 19(1): 1-8.

[17] S. Li & J. Z. Li. Hybridising human judgement, AHP, simulation, and a fuzzy expert system for strategy formulation under uncertainty. Expert Systems with Applications, 2009, 36(3): 5557-5564.

[18] L. A. Zadeh. Fuzzy logic and approximate reasoning. Synthese, 1975, 30(3/4): 407-428.

[19] L. A. Zadeh. The role of fuzzy logic in the management of uncertainty in expert systems. Fuzzy Sets and Systems, 1983, 11: 199-227.

[20] T. L. Saaty. How to make a decision: The analytic hierarchy process. European Journal of Operational Research, 1990, 48(1): 9-26.