

An Agent-Based Simulation Model of Organizational Behavior in a Firefighting Team

Yunbo Lu
School of Economics and Management
 Tongji University
 Shanghai, China
 booblu@tongji.edu.cn

Xu (Cissy) Yang
Department of Marketing and Decision Sciences
 San Jose State University
 San Jose, CA, USA
xu.yang@sjsu.edu

Abstract— An agent-based simulation model is developed to model the organizational behavior of a firefighting team. Our research interest focuses on the relationship between the distribution of authority in the firefighting team and its team performance. There are two types of authority distribution factors: self-managing factor and supervisor-centered factor. We found that a high team performance can be obtained when the self-managing factor is in the state of self-managing and the supervisor-centered factor is in the state of supervisor-centered. We also found that the self-managing factor has a major impact on the team performance.

Keywords - Agent-based simulation; firefighting; distribution of authority; team performance

I. INTRODUCTION

For many years, simulation has been successfully implemented in many industry processes, such as manufacturing and distribution. Such simulation-based approaches have many advantages: (1) understand the entire process via graphics or animation; (2) compare various alternatives without interrupting the real system; (3) compress time so that timely policy decisions can be made; (4) capture system dynamics by using probability distribution for unexpected events; (5) dramatically minimize the risk of changes in planning process by testing alternatives before implementing the changes [1].

In recent years, many researchers have shifted their research interests into an agent-based simulation realm. According to [2], there are several key application areas of agent-based techniques (Figure 1). The methodology of agent-based simulation is based on a multi-agent system, which is a cluster of individual intelligent agents interacting with each other to solve a complex, system-wide problem. A major reason that leads to this shift is that there are many interacting factors with their own functions and features which affect the process we simulated. Understanding how these factors influence the process is very critical. However, it is difficult to study the influence of various factors by using a regular simulation approach. Agent-based simulation provides the knowledge to support concurrent and distributed decision making, which is in effect simulating the individual components and the behavior that emerges through their interactions.

In this paper, we apply an agent-based simulation approach to study the organizational behavior of a firefighting and rescue artificial team (FRAT). The objective is to verify the relationship between the

distribution of authority in FRAT and its team performance.



Figure 1. Key application areas of agent-based simulation

The remainder of this paper is structured as follows. In the next chapter, we present a brief literature review of the agent-based simulation approach and the relationship between the distribution of authority and team performance. In Chapter 3, an agent-based simulation model is developed for a FRAT in order to study how authority distribution is related to team performance. An experimental design is also provided in this chapter. In Chapter 4, we analyze the computational results of the experimental design. We conclude this research and point out future directions in Chapter 5.

II. LITERATURE REVIEW

A. Intelligent Agent-based Simulation Methodology and Multi-agent Systems

There are many definitions of agents in the previous literature. We present several classic definitions of other researchers:

- An agent is an encapsulated computer system in some environment and has the ability to execute flexible and autonomous actions in its environment to obtain its design objectives [3].
- An agent is a system situated within and part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future [4].
- An agent is an autonomous, goal-oriented software process that operates asynchronously, communicating and coordinating with other agents as needed [5].
- An agent is a computer system that is either conceptualized or implemented using natural phenomena [6].

Typically, an agent has one or more of the following abilities: the ability to communicate with other software agents, the ability to learn from experience and adapt to changes in the environment, the ability to make plans and the ability to negotiate with other agents. Reference [7] summarizes some attributes of an agent: autonomy, communication ability or sociability, capacity for cooperation, capacity for reasoning, adaptive behavior and trustworthiness.

A multi-agent system (MAS) is a community of autonomous, intelligent and goal-oriented units that efficiently cooperate and coordinate their decisions with other agents to reach a higher level goal [2]. Garcia-Flores et al. point out that the MAS should be adaptable to different business processes and allow easy integration of individual components into the system [8]. According to [9], an MAS is a group of agents that cooperate with each other to fulfill common and individual goals; also agents may compete in some environments. There are four main components in an MAS: agent, environment, activity and relationship. An MAS includes cooperation, synergy, negotiation, and competition between agents [10].

Agents are autonomous in nature, which means that they could be either cooperatively working towards a common goal or selfishly acting towards achieving their own goals. Each agent has limited capabilities or incomplete information to solve the problem. Agents have their own models or algorithms to make their decisions, and parameters or indicators to express their status. They perform better than the isolated individual agents due to the cooperation and distribution of tasks between agents in the system. In an MAS, there are communication languages, interaction protocols and agent architectures to facilitate the entire system. An MAS supports more flexible and comprehensive modeling capabilities, and is able to follow the strong evolution ability of the supply chain by adding or removing agents without the need to completely reconstruct the entire supply chain. In other words, such a system is adaptive to changes within the

environment in a distributed fashion without necessarily affecting the entire system.

There are four main benefits when using agent-based methodology: feasibility, robustness and flexibility, reconfigurability and redeployability, as well as several drawbacks including cost, guarantees on operational performance, scalability, commercial platforms, engineering education, design methodologies, standards, agent system performance and misapplication [2].

In recent years, MAS has been a preferred approach to solve many complex problems, since these problems are autonomous, distributive, complex, heterogeneous, and decentralized in nature and require extensive intelligent decision making. The applications of MAS vary from the lowest level of machine control to the management of a distributed enterprise [2]. An MAS focused on systems in which various intelligent agents interact with each other could solve more complex problems than systems involving a single agent.

However, although agent-based simulation has been successfully applied in many research areas, limitations still exist. An important limitation is that most applications of this novel simulation methodology are for industry processes or physical systems, not for human organizational behavior. The area of organizational behavior needs to be explored. This is one of the most important reasons why we conduct this research.

B. The Relationship between the Distribution of Authority and Team Performance

Reference [11] points out that team design, team context and team process are three factors that affect the team performance. For the team design factor, it can be divided by three parts: team composition, task design and team structure. Many researchers state that team structure has a major impact on team performance [12]-[14]. There are three variables of team structure, which are distribution of authority, team size and structural interdependence. Figure 2 shows clearly that these three variables (distribution of authority, team size and structural interdependence) determine how a team performs. In other words, these three variables determine if the team performance is high or low in practice. In this paper, we focus our study on the relationship between the distribution of authority and team performance.

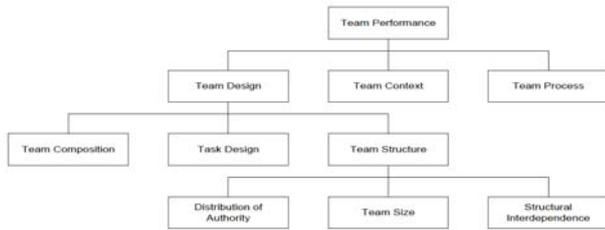


Figure 2. A hierarchy chart of team performance

Current study about the relationship between the distribution of authority and team performance concentrates on the degree of self-management. Reference [15] points out that a self-managing team is one of the most common types of teams in various organizations, which is important to improve the team performance. In most instances, self-managing teams are assigned an integrated task and then are given the authority of making decisions on how to accomplish the task. Therefore, every single team member will take the responsibility of task allocation, as well as setting objectives, determining procedures, solving problems and so on. As a result, self-managing teams can reduce the time to finish a task and improve the efficiency to make a decision. Hence, self-managing teams have a positive impact on the team performance.

In practice, it is not precise to distinguish between a self-managing team and a nonself-managing team. Instead, we measure teams by the degree of selfmanagement. Reference [16] compare self-managing teams and supervisor-centered teams. In selfmanaging teams, the functions of a supervisor are taken over by the team as a whole. In contrast, the team leader/supervisor is central to decision making in supervisor-centered teams. However, just because the team is self-managing does not necessarily imply that the team does not have a leader [17].

When we consider team design, the degree of self-management is manipulated by the configuration of authority factors. Although many researchers believe that the degree of self-management makes a large contribution to obtaining high team performance, they seldom go into details of how to define and adjust the degree of self-management. This motivated us to study how the degree of selfmanagement affects team performance. Because each team is a complex system with many autonomous and goal-oriented individuals, we propose an agentbased approach to simulate such organizational behavior.

III. AN AGENT-BASED SIMULATION MODEL FOR FRAT

We model the team performance of a firefighting team using an agent-based simulation approach. The objective is to study the relationship between the

distribution of authority in the FRAT and its team performance. Specifically, we focus our study on how to define the factors of self-management and adjust the degrees of these factors, by which different team performance can be obtained.

A. Defining Agents and A Multi-agent System

In the agent-based FRAT simulation model, there are two types of agents: firefighters and residents. We model a hypothetical community with residence buildings, roads and one fire station to serve this community. There are three types of firefighters (Table 1) and there are five types of residents (Table 2). We model such a FRAT using NetLogo 4.0.2.

TABLE I. TYPES OF THE FIREFIGHTERS

Type	Fire fighting and control	Rescuing people	Assisting rescue
Color	Red	White	Blue

TABLE II. TYPES OF THE RESIDENTS

Type	Normal	Wounded	Waiting for rescue	Being rescued	Dead
Color	Yellow	Brown	Dark brown	White (with a cross)	Black

There are two emergency exits in each building, where the residents can escape from a fire. Normally, the residence buildings are green in color. When they are on fire, the buildings change to brown. The larger a fire is, the darker that building is.

When there is a fire in one building, the residents living in that building either have the ability to perceive the fire or are informed by others of the existence of the fire. After that, the residents will call 911, escape from the building or tell other residents. If people cannot escape from the building, they may become wounded and their movement will become slow and their color will get darker.

Each resident is defined by the quality to survive. If he/she is wounded in a fire, the quality to survive is decreased. When his/her quality to survive falls into a predetermined value, he/she cannot move anymore and will wait for rescue. When the quality to survive becomes zero, he/she dies.

The FRAT contains firefighting trucks, team leaders and firefighters. Firefighters are directed by team leaders on how to rescue people, put out fires and so on. The color of the firefighters changes according to their current jobs.

B. Experimental Design

We define three types of self-management factors, which are rescue factor X_1 , fire control factor X_2 and fire put out factor X_3 . Each factor has one switch and one slider in the NetLogo developing environment. When the switch is off, its related factor is managed by the firefighters and $X_i = 0$ ($i=1$, and team leaders manage the related factors. In such circumstance, $X_i = t$ ($i=1, 2, 3, t=1, 2, 3, 4, 5$), t is the ability of their decision-making. For example, $X_1 = 2$ means that the team leader only has the ability to assign two firefighters to rescue two residents. If at that time there are more than two residents that need to be rescued, others need to wait until the next rescue.

We set a constraint on the ability of decision making of a team leader, which is $X_1 + X_2 + X_3 \leq 5$. The total number of X_i value is six, that is $X_i = 0, 1, 2, 3, 4$ and 5 . After adding such constraint, the combination of X_1, X_2 and X_3 is 56. Then we define three types of teams based on different combinations of self-management factors. They are self-managing, supervisor-centered and hybrid teams. We can compare their characteristics in Table 3.

TABLE III. THE CHARACTERISTICS OF DIFFERENT TEAMS

Team type	Self-managing	Supervisor-centered	Hybrid
X_1	0	$\neq 0$	all other combinations
X_2	0	$\neq 0$	
X_3	0	$\neq 0$	

Besides the combinations of the self-management factors, we also consider nine different sizes (4 to 12) of the FRAT, which makes the total combinations in this experimental design 504. Accordingly, there will be 504 different values of the team performance. The FRAT performance can be measured from many perspectives, such as efficiency and loss. In our research, we measure the team performance in terms of a loss value. This implies that the smaller the loss is, the better FRAT performs.

IV. COMPUTATIONAL RESULTS

A. The Relationship between the Degree of Selfmanagement and Team Performance

In Table 4, P_{loss} is the average loss performance of all circumstances under each team type (selfmanaging, supervisor-centered and hybrid). The degree of self-management in a self-managing team is the highest among these three types of teams and the degree of self-management in a supervisorcentered team is the lowest. This table clearly shows that the higher the degree of self-management is, the better the team performance is (recall that the team performance is measured by loss performance, good team performance means low loss performance).

TABLE IV. LOSS TEAM PERFORMANCE OF THREE TYPES OF TEAMS

Team type	Self-managing	Supervisor-centered	Hybrid
P_{loss}	5,163,019.77	5,720,594.57	5,490,138.56

B. The Relationship between the Individual Selfmanagement Factor and Team Performance

We study each individual self-management factor from two perspectives: (1) for a particular selfmanagement factor, if self-managing or supervisorcentered condition leads to a better team performance; (2) if a self-management factor is under self-managing condition, how the ability of its decision-making affects the team performance.

Table 5 shows that when X_1 is under supervisorcentered condition, the team has a better performance. Similarly, when X_2 is under supervisor-centered condition, team performs better. However, when X_3 is under self-managing condition, FRAT has a higher performance than when X_3 is supervisor-centered. Based on this result, we can define X_1 and X_2 as supervisor-centered factors and X_3 as self-managing factor.

TABLE V. LOSS TEAM PERFORMANCE FOR EACH SELFMANAGEMENT FACTOR UNDER TWO CONDITIONS

P_{loss}	Self-managing	Supervisor-centered
X_1	5,834,229.26	5,237,968.39
X_2	5,668,464.82	5,341,251.93
X_3	4,810,385.79	5,901,397.99

Figures 3, 4 and 5 show that: (1) the higher X_1 's ability of decision-making is, the better team performance is; (2) when the ability of decisionmaking for X_2 is the highest, the best team performance is obtained. But the worst team performance is not obtained when the ability of decision-making for X_2 is the lowest; (3) the best team performance is obtained when the ability of decision-making for X_3 is 3.

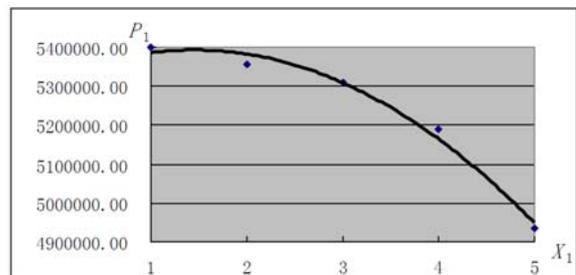


Figure 3. The ability of decision-making for X_1 vs. team Performance

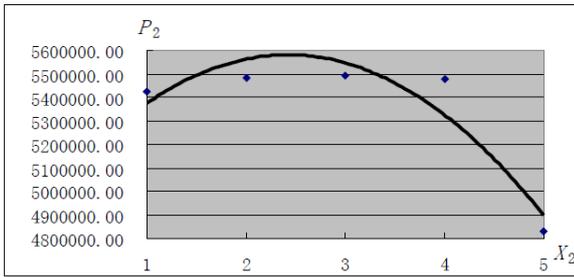


Figure 4. The ability of decision-making for X2 vs. team performance

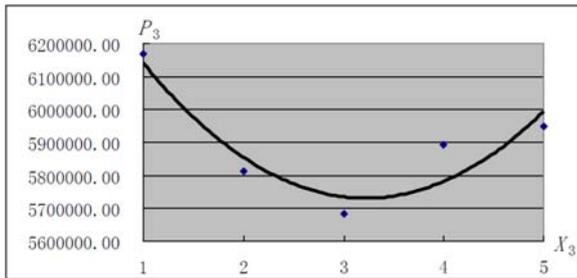


Figure 5. The ability of decision-making for X3 vs. team performance

C. The Relationship among Three Self-management Factors

We use a loss performance matrix to study the relationship among these three self-management factors: rescue factor X1, fire control factor X2 and fire put out factor X3.

Based on Tables 6, 7 and 8, we find that:

- 1) The larger the sum of the ability of decisionmaking for supervisor-centered factors (X1 and X2) is, the better the team performance is.
- 2) When X1+X2 is a certain number (both X1 and X2 are not zero), the bigger X1 value is, the better the team performance is. In other words, when supervisor-centered factors are under supervisor-centered condition, if the total ability of decisionmaking of them is a certain amount, increasing the ability of decision-making for X1 will increase the team performance. This also means X1 weights more than X2 in teams of increasing team performance.

V. CONCLUSION AND FUTURE DIRECTIONS

According to Marik and McFarlane, there are several key application areas of agent-based techniques:

- Real-time control of high-volume, highvariety, discrete manufacturing operations;
- Monitoring and control of physically distributed systems;
- Transportation and material-handling systems;
- Management of frequently disrupted operations;

- Coordination of organizations with conflicting goals;
- Frequently reconfigured, automated environments [2].

In this paper, we develop an agent-based simulation model to study the performance of a firefighting team. We define three types of selfmanagement factors: rescue factor X1, fire control factor X2 and fire put out factor X3. We also define X1 and X2 as supervisor-centered factors and X3 as self-managing factor. Results show that a high team performance can be obtained when the self-managing factor is in the state of self-managing and the supervisor-centered factor is in the state of supervisor-centered. The relationship between the distribution of authority and team performance is nonlinear. We also found that the self-managing factor has a major impact on the team performance. We propose to study the relationship between other team structure variables (team size and structural interdependence) and the team performance in the next step.

REFERENCES

- [1] Chang, Y., and Makatsoris, H. 2001. Supply chain modeling using simulation. *International Journal of Simulation* 2(1): 24-30.
- [2] Marik, V., and McFarlane, D. 2005. Industrial adoption of agent-based technologies. *Intelligent Systems* 20(1): 27-35.
- [3] Wooldridge, M., and Jennings, N. 1995. Intelligent agents: theory and practice. *Knowledge Engineering Review* 10 (2): 115-152.
- [4] Franklin, S., and Graesser, A. 1996. Is it an agent, or just a program?: a taxonomy for autonomous agents. *Proceedings of the Third International Workshop on Agent Theories, Architectures, and Languages*: 21-35
- [5] Fox, M.S., Barbuceanu, M., and Teigen, R. 2000. Agentoriented supply-chain management. *International Journal of Flexible Manufacturing Systems* 12(2-3): 165-188.
- [6] Tiejun, M., and Yoshiteru, N. 2005. Agent-based modeling on technological innovation as an evolutionary process. *European Journal of Operational Research* 166(3): 741-755.
- [7] Nissen, M. 1995. Intelligent agents: a technology and business application analysis. *Telecommunications and Distributed Processing*, November, 1995.
- [8] Garcia-Flores, R., Wang, X.Z., and Goltz, G.E. 2000. Agent-based information flow for process industries' supply chain modeling. *Computers & Chemical Engineering* 24(2-7): 1135-1141.
- [9] Davidsson, P., Henesey, L., Ramstedt, L., Tornquist, J., and Wernstedt, F. 2005. An analysis of agent-based approaches to transport logistics. *Transportation Research Part C* 13(4): 255-271.
- [10] Dong, S.H., Xi, B., Tian, L.N., Huang, Q.G., and Chen, H.X. 2006. An agent-based architecture for supply chain management. *Proceedings of the Fifth International Conference on Machine Learning and Cybernetics*: 137-141.
- [11] Hackman, J.R. 1987. The design of work teams. *Handbook of Organizational Behavior*, 315-342. Lorsch J, NJ: Prentice-Hall.
- [12] Cohen, S.G., and Bailey, D.E. 1997. What makes teams work: group effectiveness research from the shop floor to the executive suite. *Journal of Management* 23(3): 239-290.
- [13] Wageman, R. 1995. Interdependence and group effectiveness. *Administrative Science Quarterly* 40(1): 145-180.
- [14] Werner, J.M., and Lester, S.W. 2001. Applying a team effectiveness framework to the performance of student case teams. *Human Resource Development Quarterly* 12: 385

[15] Lawler, E.E., Mohrman, S.A., and Ledford, G.E. 1995. Creating high performance organizations: practices and results of employee involvement and total quality management in Fortune 1000 companies. San Francisco: Jossey-Bass.
 [16] Dunphy, D., and Bryant, B. 1996. Teams: panaceas or prescriptions for improved performance? Human Relations 49: 677-699.

[17] Stewart, G.L., and Barrick, M.R. 2000. Team structure and performance: assessing the mediating role of intrateam process and the moderating role of task type. Academy of Management Journal 43: 135-148.

TABLE VI. X1- X2 LOSS PERFORMANCE MATRIX

P_{12}		X_1						
		self-managing	supervisor-centered					
		0	1	2	3	4	5	
X_2	self-managing	0	5,969,584.61	5,564,551.61	5,624,157.13	5,637,054.81	5,527,097.02	4,935,510.00
	supervisor-centered	1	5,884,928.62	5,334,618.97	5,266,960.19	5,134,431.68	4,514,339.20	
		2	5,828,801.49	5,401,078.03	5,305,843.86	4,681,838.29		
		3	5,830,671.83	5,414,230.83	4,645,131.41			
		4	5,819,651.32	4,793,215.88				
		5	4,830,141.68					

TABLE VII. X1- X3 LOSS PERFORMANCE MATRIX

P_{13}		X_1						
		self-managing	supervisor-centered					
		0	1	2	3	4	5	
X_3	self-managing	0	4,967,677.35	4,783,634.01	4,694,204.85	4,710,562.66	4,724,924.85	4,935,510.50
	supervisor-centered	1	6,521,082.39	6,037,748.74	5,934,352.38	5,936,603.86	6,118,683.55	
		2	6,056,780.65	5,550,864.63	5,694,493.78	5,856,970.37		
		3	5,991,357.30	5,272,983.77	5,585,464.09			
		4	5,979,152.25	5,718,421.93				
		5	5,947,839.40					

TABLE VIII. X2- X3 LOSS PERFORMANCE MATRIX

P_{23}		X_2						
		self-managing	supervisor-centered					
		0	1	2	3	4	5	
X_3	self-managing	0	4,982,478.71	4,628,767.79	4,741,522.48	4,763,084.45	4,946,952.76	4,830,141.68
	supervisor-centered	1	6,228,967.28	5,977,493.43	6,138,477.70	6,271,249.55	6,538,613.00	
		2	5,854,539.22	5,708,375.26	5,724,267.80	6,133,856.18		
		3	5,660,915.78	5,570,423.02	5,981,910.14			
		4	5,824,654.43	6,027,417.57				
		5	5,947,839.40					