EXAMINING COMPLEX SYSTEMS AND AGENT-BASED MODELING FOR IMPROVING DECISION MAKINGS IN CONSTRUCTION ORGANIZATIONS

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ABSTRACT

The management on construction projects and organizations is very important. However it is poorly understood considering the declining performance of construction industry. Managing and predicting the work performance of a construction organization tends to be extremely difficult using conventional management approaches. This paper regards construction as a complex system and proposes the use of Agent-Based Modeling (ABM) as a management enhancement tool for construction organizations. Building on an organizational simulation platform proposed by the authors (Virtual Organizational Imitation for Construction Enterprises, VOICE), the influence of human and organizational factors on work performance has been investigated. Additionally, different management scenarios of a case study in construction bidding have been examined using a complete management cycle, Plan-Simulation-Check-Action (PSCA). The results indicated the new management tool can easily help decision makers to streamline processes, manage human resources, and testify any changes at real time. It demonstrated better practicability than conventional management. This paper highlighted the value of the proposed approach on managing construction organizations.

Keywords: complex system, project management, agent based modeling, decision making

1. INTRODUCTION

Construction industry is in general suffering significant performance problems: productivity is dropping (Teicholz et al. 2001); time/cost overruns are common (Flyvbjerg et al. 2003); change orders and claims are frequent (Ren et al. 2001); and business failure rate is extremely high (Knaup and Piazza 2007). A widely accepted explanation for the declining performance is the poor standard and ineffectiveness of conventional project management (Shenhar and Dvir 2007). In fact, conventional project planning and control techniques, e.g., CPM/PERT based techniques, have been criticized for not meeting the requirement of current projects (Kidd 1991). Increasing studies indicate there is little evidence that the application of conventional project management can produce better outcome today (Pinto and Slevin 1988; Crawford 2001; Morris 2001). For example, Schenhar and Dvir (2007) observed more than 200 projects around the world and found that although most projects are well planned and managed, they failed to meet their objectives; while sometimes, even poor planning may not necessarily lead to a project's failure (Shenhar and Dvir 2007).

One possible reason for this is the increasing 'complexity' of today's projects. Traditionally, the process of construction projects is regarded as an ordered, linear system, which can be planned, controlled and managed top down (Bertelsen 2003). However, the performance issues mentioned above give rise to a thinking that the process of construction projects may be not as ordered and predictable in its nature as it may look. Closer examinations revealed that construction projects are indeed complex, nonlinear and dynamic phenomenon, or complex systems (Bertelsen 2003). It has been found such complexity not only comes from the growing uncertainties in both technology and processes (Chan et al. 2004), but also from the increasing influence of intangible organizational and human factors (Arditi et al. 2000; Ellis and Thomas 2003; Westerveld 2003). As a result, recent literature suggests the process of construction projects should be studied from the complex systems' point of view, and new project management models that can reflect such complexity are needed (Bertelsen and Koskela 2002; Bertelsen 2003; Thomassen et al. 2003; Schalcher 2009).

This paper proposed the use of Agent Based Modeling (ABM) for enhancing the management in construction organizations as complex systems considering the impacts of organizational and human factors. At first, we examined the nature of construction, and the status quo of decision making and ABM applications in construction area. Then a simulation based project management methodology was proposed. Finally, a case study was demonstrated as an example that how the proposed methodology works. Especially, we introduced how to use a simulation model developed by the authors (named Virtual Organizational Imitation for Construction Enterprises, VOICE) to improve the management of bidding decision making under several scenarios.

2. BACKGROUND

2.1. Construction as a complex system

Although there is a steady growing of literature about complexity science and complex systems, a common definition of 'complexity' is still missing (Mitchell 2009). Despite, most literature concludes complex systems have certain common features (Waldrop 1992; Kauffman 1995; Lucas 2000; Johnson 2002). Johnson et al. (2003) summarized the common features of a complex system as: (1) Feedback: output in the past will influence an occurrence in the present or future; (2) Non stationary: not like a perfect statistical system, a complex system's future behavior is unpredictable to some extent; (3) Many interacting agents: the system contains many autonomous entities known as "agents", which interact with each other; (4) Adaptation: an agent can adapt its behavior towards better award or performance; (5) Evolution: as a result, the system evolves and remains far from equilibrium, driven by ecology of agents who interact and adapt under the influence of feedback; (6) Single realization: every studied system is a single realization; and (7) Open system: Systems are continuously open to new information from the environment and circulating the information within the system will continuously change in response. Besides, most literature also claim that 'emergence' is another property of complex systems that would be summarized as 'the whole is greater than the sum of the parts (Waldrop 1992; Kauffman 1995; Lucas 2000).

In construction area, although there is no clear answer about what "complexity" meant to construction either, literature has already started to explain where such complexity comes from. Schalcher (2009) concluded that the complexity in construction are from two aspects: system and process. The former one refers to the highly interacted components of a construction system, i.e., interdependence of subsystems; while the later one refers to the entire construction processes and the activities happen among it. Studies of Critical Success Factors (CSFs) proved that increasing human and organizational factors account for the success of construction projects and organizations and therefore increase the complexity (Mengesha 2004). Bertelsen (2003) summarized that the complexity in construction are from three aspects: project itself, interdependent parties of a project team, and human factors with social interaction.

Moreover, increasing literature started to study the construction system and process from the complex systems' point of view. Wild (2002) focused on the social system since it is the source of management complexity in construction. Meanwhile, other scholars began to study the similarity between construction systems and complex systems: Bertelsen (2003) compared the features of construction system and process with the common characteristics of complex systems, and concluded that construction should be regarded as a complex system. Schalcher (2009) listed the complexity of different construction processes and scales, and argued that management in construction should take all the complexities into account.

2.2. Project management models

Project management roots from the field of operations research of the 1940s and 1950s (Morris, 1997). Since then, conventional project management is based on the idea of optimizing project objectives (Bredillet and Liie 2007). Network based optimization tools include the critical path methods (CPM) and program evaluation and review technique (PERT), and graphical evaluation and review technique (GERT). For a considerable period, these techniques have improved the performance of construction projects significantly. Therefore, project management, or the set of standard management techniques on projects, has been regarded as formal managerial discipline and well developed. Currently most construction projects are planned and executed very well following a specified of rules (Shenhar and Dvir 2007).

Giving the awareness of construction as a complex system, new project management models have been proposed. By concluding the complex nature of construction processes, Sterman (1992) proposed a new project management model which can reflect the dynamic and nonlinear construction processes. In the proposed system dynamic model, there are multiple interdependent components, multiple feedback processes, and involves both hard and soft data for decision making. Jaafari (2003) claimed that project management is "supposedly to be a systemic approach to management of change", but the foundation of current project management "lies in the traditional rational managerialism thus facing an increasing threat of irrelevance". Therefore, Jaafari proposed a new project management model, or 'creative-reflective' project management model that incorporates the requirements of environment and project complexity: open system, chaos, self-organization and interdependence (Jaafari 2003). In the book '*The new project management*', Frame (2002) commented that the conventional project management (e.g., PERT, S-curve analysis, resource allocation techniques) is no longer suitable for the 'chaotic world'. He proposed a set of new ways to cope with the 'complexity' and 'change' of today's projects. Most of these contributors advocated the importance of complexity thinking though, specific complexity oriented management tools haven't been proposed rather than new management principals.

2.3. Agent based modeling

Agent Based Modeling (ABM) is a suitable tool for use of studying complexity (North and Macal 2007). As a computational modeling approach, ABM can be used to study the emergent property of socio-technical systems by simulating the simultaneous actions of various autonomous individuals, or agent, in a system (Macal and North 2007). In organizational studies, different from top-down modeling approaches (e.g., System Dynamics, Discrete Event Simulation etc.), it means the collective behaviors of an organization are not predefined, but emerge from individual agents who act based on what they perceive to be their own interests. Using this framework, the performance of construction enterprises and projects are the outcomes of a number of accountable factors, distinct activities, and interactions among them.

Applications of ABM are numerous and diverse. As to construction area, Several ABM models specifically designed for construction enterprises have been developed and validated (Jin and Levitt 1996; Ortiz de Orue et al. 2009; Unsal and Taylor 2009); Among them, Virtual Design Team (VDT) developed at Stanford University is one of the most influential (Jin and Levitt 1996). By marrying the organizational structure with a project's task precedence diagram, VDT analyzes how interdependencies between sequential and parallel activities raise coordination needs, and how organization and communication tools may change the coordination capacity of project teams (Jin and Levitt 1996). As a well-documented and well-validated organizational simulation tool, it is widely applied to study project based organizations to estimate project durations, costs, and quality. Many models have been extended from VDT to investigate organizational learning, project network dynamics, integrated technology impacts, and organizational alignment (Ortiz de Orue et al. 2009; Unsal and Taylor 2009; Wong et al. 2009). In spite of the success of these models, some shortcomings question their applications. For example, some models concentrate only on macro-level simulation, which has little help for studying "one-company-scope" issues. In the micro-level models, however, too many assumptions are made to simplify the problems: for instance, only one project scenario is considered; only one or two agents are in the model; and agent behaviors are highly simplified. In contrast, reality is more complex: most construction enterprises face multiple projects simultaneously; the work performance depends on many determinants, e.g., individual decision preference, institutional affects, work arrangements, environmental impacts; micro-level activities interact, leading to uncertain consequences; and behaviors and values significantly differ among typical roles within a company (e.g., president, managers and average employees).

3. METHODOLOGY

The proposed new project management model is extended from a widely used business re-engineering methodology, or Plan-Do-Check-Action (PDCA) method. First, a ABM simulation model was developed to represent the organizational structure, business process and human decision making process of the studied construction organization; then, a method extended PDCA was proposed on the basis of the simulation model, named Plan-Simulate-Check-Action (PSCA).

3.1. Building simulation platform

An ABM simulation platform constitutes the basis of the proposed project management method. This paper utilized an ABM simulation model developed by the authors, named Virtual Organizational Imitation for Construction Enterprises, or VOICE (Du and El-Gafy 2010). VOICE is a multi-agent model which aims to reproduce the real world activities of construction enterprises in the desktop computer. It can be used in predicting project performance (e.g., time/cost/quality), process performance (e.g., effective work ratio, work mistakes in work process etc), as well as employee performance (e.g., contribution of every staff, work pressure of every staff etc.). By simulating detailed micro-level work processes and human decision processes inside one construction enterprise (e.g., one contractor), performance as emergent phenomenon of many interrelated complicated behaviors can be represented. The theoretical base of VOICE is the “basic model for organizational behavior” proposed by Robbins and Langton (Robbins and Langton 1998). According to Robbins and Langton, work performance is emerged from a dynamic process: the beginning of the process is human beings with various personality, ability, values, perceptions and motivations etc. Then individuals form a team with similar target and interest, and teams further interacted with each other generate organizational phenomenon. Finally, work performance is generated as the results of the entire process. Using VOICE, what-if scenarios simulation can be achieved.

3.2. Plan-Simulation-Check-Action

Plan-Do-Check-Action (PDCA) is a widely used business re-engineering management loop. The concept of PDCA is from scientific method, i.e., to validate any changes should be along "hypothesis" - "experiment" - "evaluation" or plan, do, and check (Deming 2000). The steps of conducting PDCA is: (1) Plan. Establish the objectives and processes necessary to deliver results in accordance with the expected output; (2) Do. Implement the new management practices in a small scale if possible; (3) Check. Measure the new management practices and compare the results against the expected results to ascertain any differences; (4) Act. Analyze the differences and determine their cause. By repeating these four steps, a continuous improvement loop is formed. This paper utilizes the same logic of PDCA, but substitute the “do” with “simulation”, i.e., using experimental simulation replace the real world feedback. As a result, the proposed project management method is a Plan-Simulation-Check-Action (PSCA) cycle, with cooperation between decision makers and model developers. The specific process is: (1) Plan. The decision makers propose the concrete management objectives to the model developer. For example, improve the quality of work, reduce the time, or level the work-related stress of employee. (2) Simulation. Based on the requirements of decision makes, as well as interviews, surveys and observations on the real construction enterprises, the model developer modifies the simulation model to reproduce the studied enterprise. (3) Check. Together with the model developer, the decision maker observes the consequences of proposed management practices, decisions, processes and etc., and identifies better choices. (4) Action. Based on cost-benefit analysis, the decision maker makes the final decision of changes. In the following section, we use a case study to demonstrate how PSCA works.

4. CASE STUDY

4.1. Modeling and simulation

Company A is a small developer located in Michigan. There are three departments (project planning, project management and accounting) and 11 person in this company. As a developer though, this company is also conducting for their own projects, such as new construction or maintenance. One of the major tasks of this company is looking for new projects and bidding for interested projects. The principals (presidents) of this company wants to know how to improve the efficiency of their bidding process, and meanwhile, without overloading their employees. Based on the time sheets provided, semi-structured interviews and online surveys, we collected the data of this company and built the simulation model as following. Figure 1 is the graphic user interface of the simulation model.

As we can see in figure 1, the following information of company A was modeled and simulated: (1) A three-level authority structure or report structure: Two principals at the top of the company (since the job responsibilities and decision making process of these two principals are similar, they are viewed as one role, president, in the model); three managers taking charge of planning department, project management section and accounting department. Also, there are several full time/part time helpers (figure 1). The black solid lines demonstrate the report structure. (2) Work: considering bidding for three projects simultaneously, a set of tasks are defined for each of the project. For example, task 1 is principal studies potential opportunity, task 2 is project planning manager contact subcontractors etc. Then these tasks are assigned to corresponding responsible actors. The blue dash lines demonstrate the work assignment and process. (3) Information flow: in some cases, to make a particular decision or finish a task need extra information. For example, preliminary estimation needs information employee payment quote from accounting section. The red dotted lines show how actors exchange information. (4) human traits: such as work competence (efficiency of work), work quality, work-related preference, capacity (available work time) and etc. (5) decision process: this is not shown in figure 1, but embedded in the simulation model. Decision process in this model is the way individuals make their decisions under different scenarios. For example, project planning manager (manager 1) can either assign a particular task to the faster helper (staff 1), or to the better helper (staff 2). The final decision based on his/her preference. Or when manager 1 found the quality of work submitted by helpers is not satisfied, he/she could either return the job or correct some mistakes by self based on preference and current situation (e.g., bidding deadline).

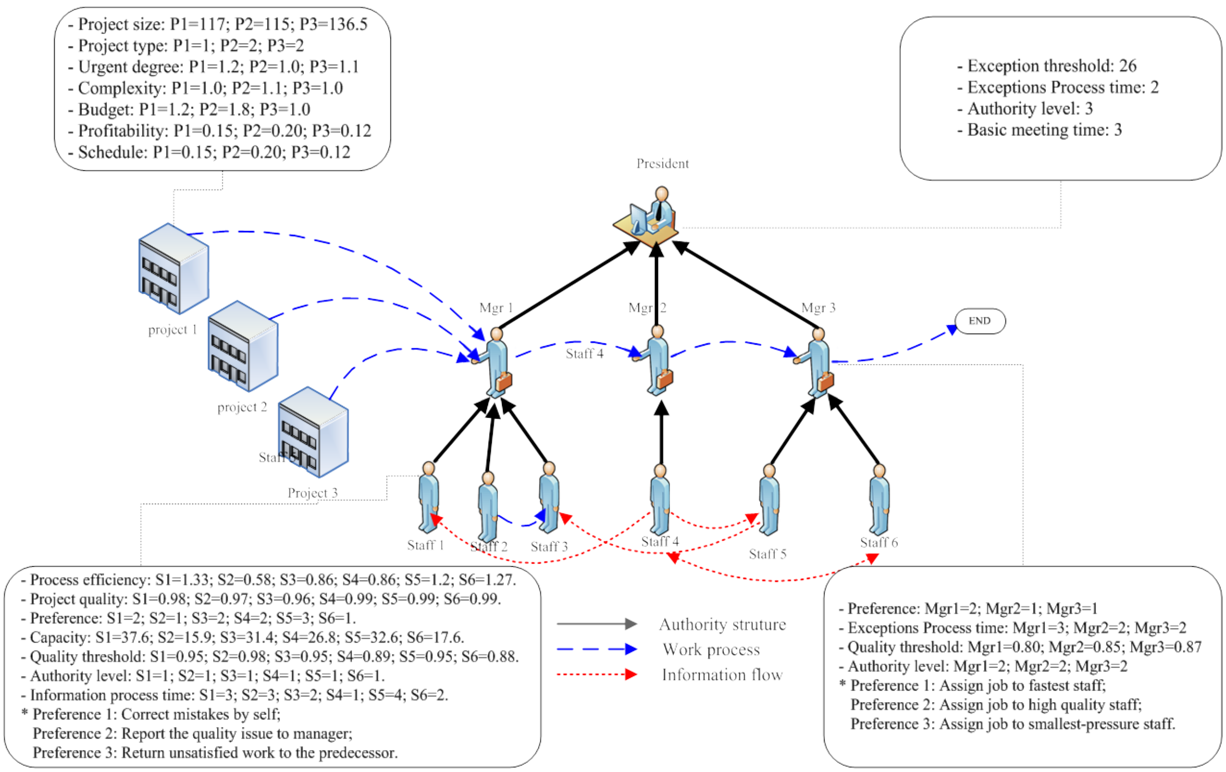


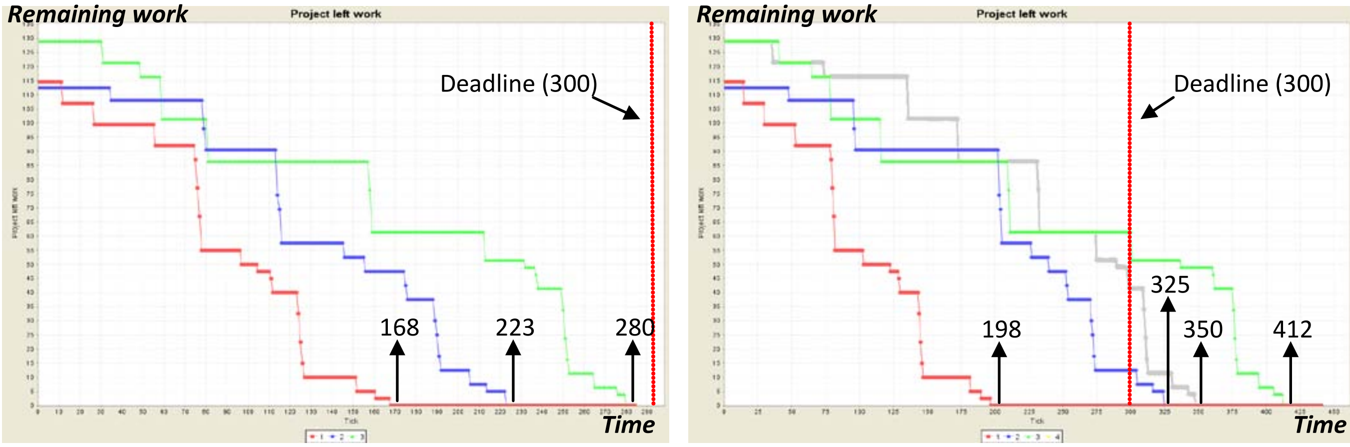
Figure 1: The input-process-output framework of construction enterprises

Validated by the principals of this company, we have conducted several simulations under different management scenarios to testify management practices.

4.2. Scenario 1: more projects vs. less projects

Company A is bidding for three projects simultaneously; but the principals want to know whether they can bid for extra projects based on current human resources and processes. We assume the extra project (project 4) has the same parameters and processes as project 3, and all human factors such as work efficiency stay the same under two scenarios. The simulation results showed in figure 2, where Y axis refers to the remaining work need to be done, and X axis is the elapsed time measured in tick whereby one tick equals to one hour in the real world. Therefore the real time project bidding work progress were shown.

From the simulation results we can see: when biding for 3 projects simultaneously, all the bidding work can be finished before the deadline (figure 2: suppose the deadline is 300 ticks, or 300 hours). However, when bidding for 4 projects, three of them cannot be finished before deadline (figure 2), even though only one project is added into the work list. Moreover, we found the increase of work time is not a linear relationship with number of projects: the increased total work time is more than project 4's need due to the interactions among projects. Therefore, we obtain two conclusions: (1) there is interferences among projects, which leads to more work time; (2) based on current available human resource, company A should only bid for 3 projects simultaneously.



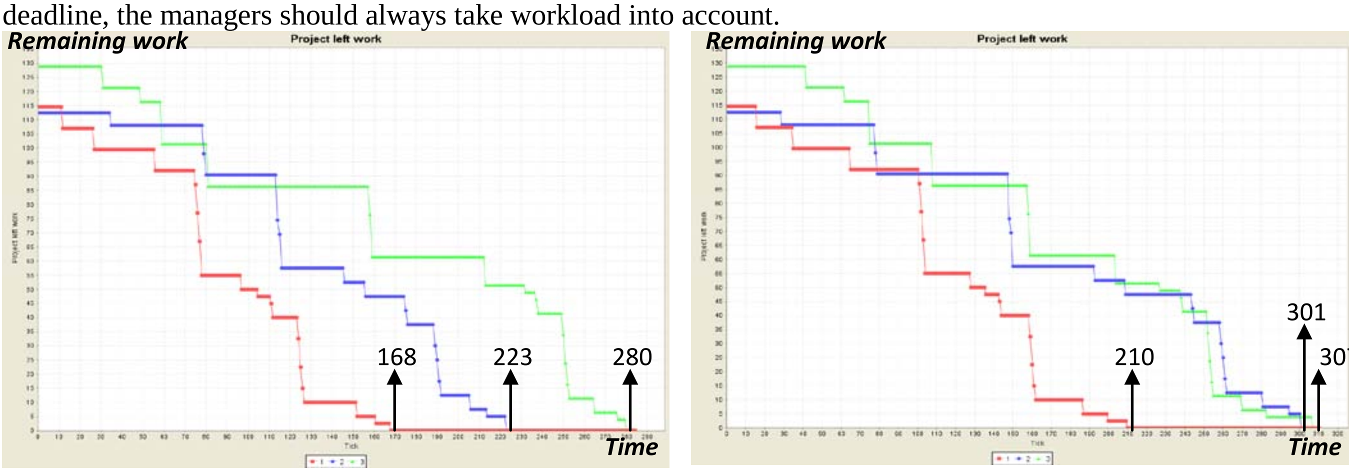
(1) Bidding for 3 projects simutaneously (2) Bidding for 4 projects simutaneously

Figure 2: real time bidding work progress (scenario 1)

4.3. Scenario 2: assigning job with consideration of helper's workload vs. assigning job to faster helper

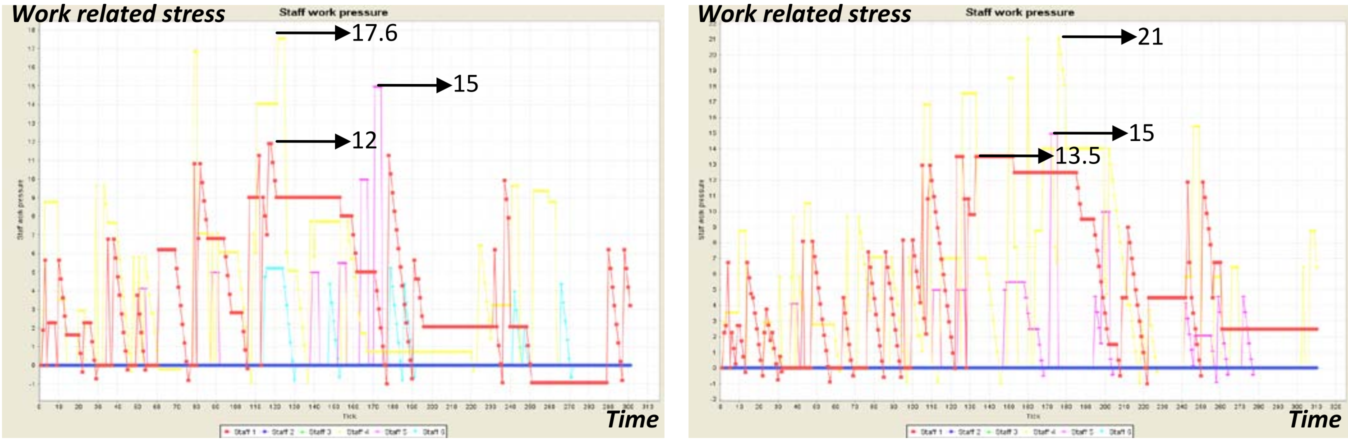
Scenario 2 is associated manager's preferences. After getting new jobs, managers assign them to their helpers. There are two major preferences: (1) assigning jobs to the helpers with least workload, and (2) assigning jobs to the faster helpers. Which preference is better, when the deadline is approaching?

We run simulations under two preferences respectively while keeping other parameters at the same. Surprisingly, assigning jobs to faster helpers does not always lead to faster finish. As shown in figure 3, always assigning jobs to faster helpers increased total work time for all the three projects ultimately, and two of the three projects bidding work even couldn't be finished on time. Why this contradiction happens? Figure 4 shows the work related stress (for the definition, please refer to Du and El-Gafy, 2010) of helpers. Under preference 1 (considering the workload), the biggest stress indicator is 17.6, happened in helper 4; but under preference 2 (always assign jobs to faster helpers), this indicator is 21. According to our interviews and observations, bigger work related stress reduces the work efficiency, and makes helpers refuse to work under some condition which means the manager has to spend extra time to reassign the job. Thus, even though company is approaching deadline, the managers should always take workload into account.



(1) assign job while considering helpers' workload (2) always assign job to faster helpers

Figure 3: real time bidding work progress (scenario 2)



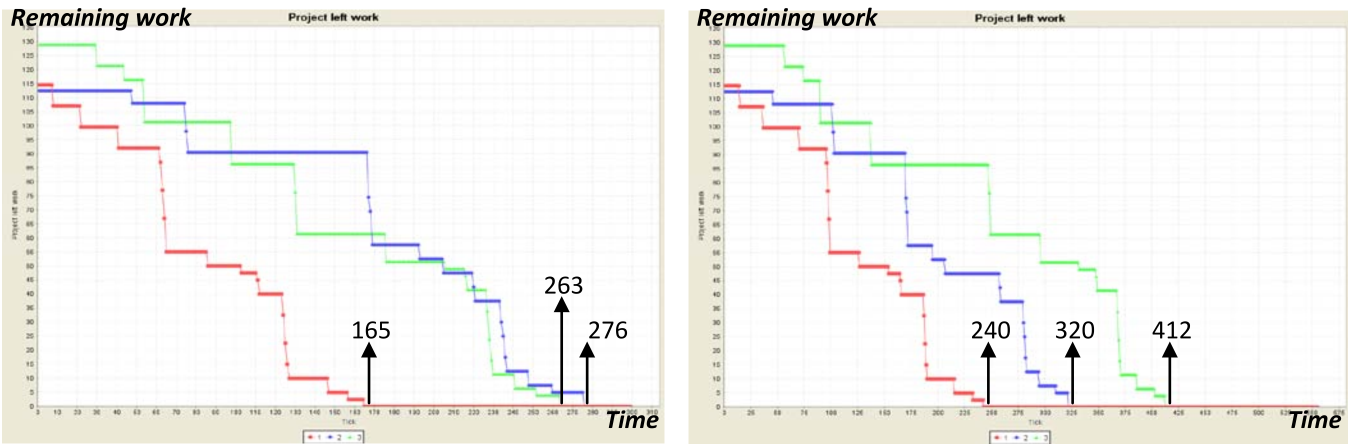
(1) assign job while considering helpers' workload (2) always assign job to faster helpers

Figure 4: work related stress of helpers (scenario 2)

4.4. Scenario 3: more trust vs. less trust

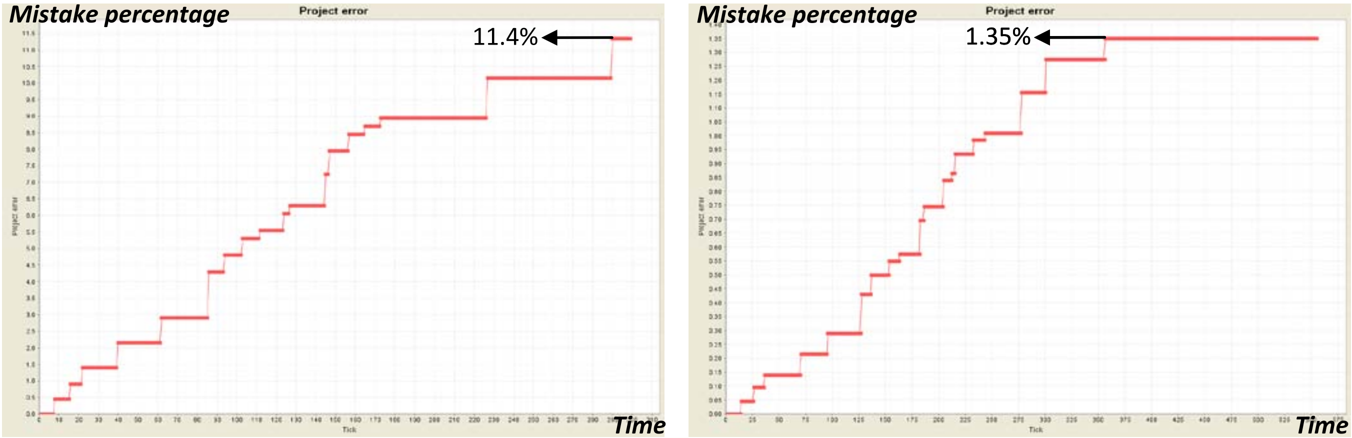
When a manager receives the submitted/delivered work finished by his/her helpers or other departments, he/she will compare the quality of the submitted/delivered work with his/her threshold. If the quality is not satisfied, he/she will return the work or correct the mistakes based on the preferences, and therefore waste more time. The threshold of the managers determine the trust degree: managers with more trust on the helpers' and other departments' work tend to accept the work without more careful check; while managers with less trust tend to be more strict on the quality of the submitted/delivered work. What's the impacts of managers' trust degree on the bidding work performance?

We suppose all the helpers make 10% mistakes on their work, and run simulations under two scenarios: (1) more trust, i.e., managers can accept work with less than 15% mistake, and (2) less trust, i.e., managers can only accept work with less than 2% mistake. Figure 5 shows the bidding work progress under two scenarios and figure 6 shows the average mistake percentage of final submitted work. As we can see, more trust leads to faster finish, but relatively high mistake percentage. There is a trade-off between the speed of bidding work and the quality of bidding work. Decision makers can use VOICE to make their trade-off.



(1) more trust scenario (2) less trust scenario

Figure 5: real time bidding work progress (scenario 3)



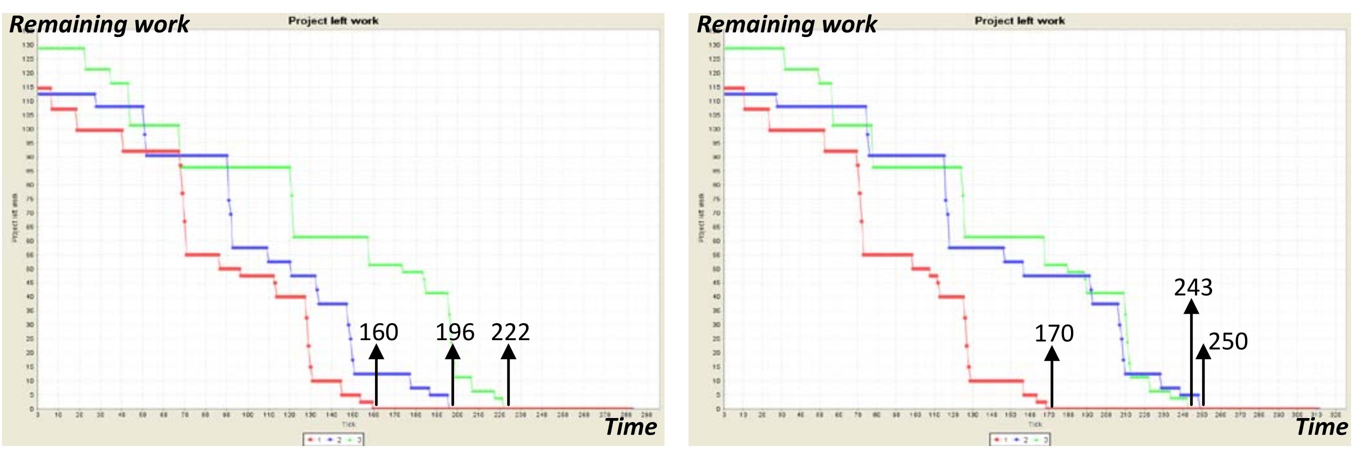
(1) more trust scenario (2) less trust scenario

Figure 6: average mistake percentage of final submitted work (scenario 3)

4.5. Scenario 4: more emergent meetings vs. less emergent meetings

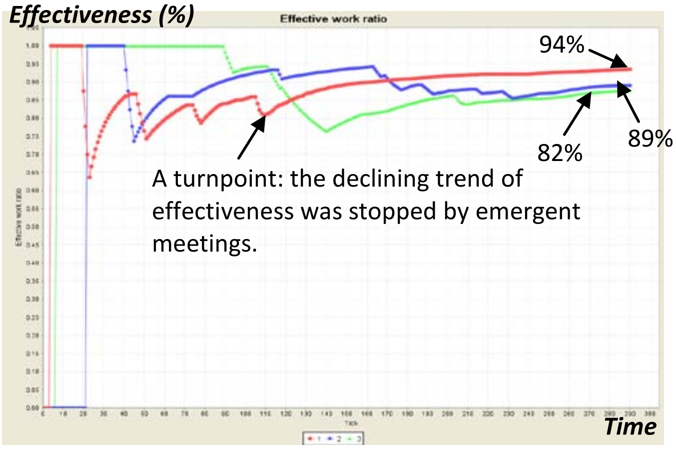
In company A, principals have the right to hold emergent meetings when they perceive too many management exceptions. These exceptions include but not limited to: approval requests from helpers and managers, reports on job burnout, lack of necessary information, conflicts between different departments etc. When the management exceptions are over the threshold of the principals, they will initiate emergent meetings. During the meetings, all employees have to pause their work for a given time though (depending on how many problems to solve), after the meetings, the problems are solved. For example, an assistant estimator will find it is much easier to get the worker payment information from the accounting department during the meeting; or the principals will announce the rules of determining profitability during the meeting so that employee needn't to ask such information repetitively. The principals want to know, however, the impacts of the frequency of the emergent meetings.

We considered two strategies: (1) more emergent meetings: we set the threshold of principals to 5, which means they are more sensitive to the management exceptions; (2) less emergent meetings: we set the threshold of principals to 50, which means they are more tolerant to the exceptions. Interestingly enough, more meetings does not necessarily lead to longer total work time: even though holding emergent meeting 'waste' extra time, the simulation results showed strategy 1 (more emergent meetings) reduced the total work time of all the three projects (figure 7). The reason is more emergent meeting benefited this company by increasing the accumulative work effectiveness (measured in the ratio of effective work time versus ineffective work time, where total time is the sum of effective work time, ineffective work time and idle time); additionally, the effectiveness indicators under strategy 1 seems more stable than under strategy 2. It means more emergent meetings don't affect employees' work; rather, it improves the efficiency. Therefore, we advise the principals of company A being more serious about the management exceptions.

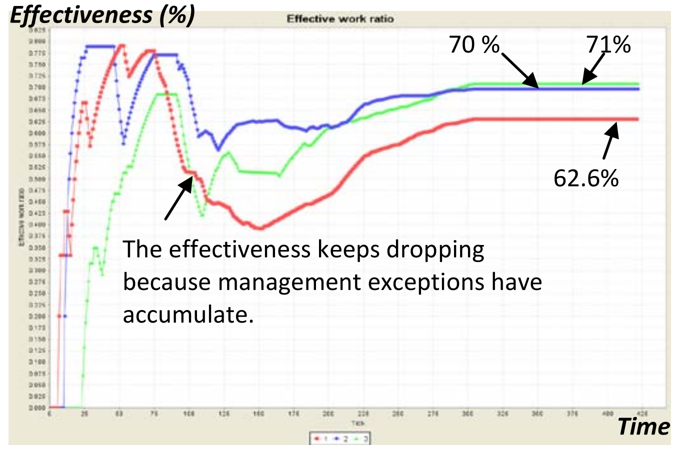


(1) more emergent meetings (2) less emergent meetings

Figure 7: real time bidding work progress (scenario 4)



(1) more emergent meetings



(2) less emergent meetings

Figure 8: accumulative effectiveness of bidding work (scenario 4)

5. DISCUSSION AND CONCLUSION

There is a growing awareness that conventional project management cannot support the complex construction process and systems in a complexity era. Increasing evidence indicates construction should be regarded as a complex system. Correspondingly, project management should reflect and cover the new features of today's projects. This paper proposes the use of computer simulation, especially, Agent Based Modeling (ABM) to enhance the management on projects and construction organizations since ABM is a perfect tool for capturing the complexity of decision makings in construction. From the case study we can see, ABM is suitable for supporting the management in construction area. Based on an ABM simulation model developed by the authors (Du and El-Gafy 2010), questions such as "how many projects I can bid at the same time?", "should we give more trust on our employees?" can be answered and testified in a convincing way. It shows that the proposed project management technique, or PSCA does support decision makings in context of complexity.

The proposed simulation-based project management has the potential to have a transformative impact on our understanding of organizational natures of construction enterprises because it touches on several basic issues: (1) Provide a comprehensive micro-level analysis platform for understanding and managing the complexity of construction; (2) Provide a user-friendly interface to practitioners, making the management more reliable and efficient; (3) Provide a simulation tool to predict and validate the impacts of newly emerged business practices and innovative technologies, especially for the construction enterprises which need to evaluate the risk to transform, to change strategy, to update technology and to reform business practices; and (4) "What-if" organizational design may be applied using the proposed platform.

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