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Team Efficiency Estimation for Construction Process Considering the Collaborative Behaviors

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Abstract

A larger construction project requires the involvement of more professionals in the project team. The efficiency of collaborative interactions among heterogeneous professionals during construction is critical to project success. A social-network-based simulation tool can assist project managers in experimenting and analyzing the efficiency of project teams. Accordingly, this study adopted the social network philosophy to create a team member interaction mechanism and applied the agent-based modeling and simulation approach to develop an agent-based project team collaborative efficiency simulation (PTCES) model for estimating the collaborative efficiency of project teams. In the PTCES model, agents with their collaborative network can execute assigned activities collaboratively so that the team efficiency can be estimated by the simulation manner. An actual building construction case was examined experimentally to calibrate and validate the proposed model, and the results proved the quantitative ability of the PTCES model in estimating team efficiency under different circumstances. The case simulation results also indicated the importance of developing a collaborative culture and reducing the reworking risk for improving the project efficiency. Moreover, a higher collaborative network density was determined to engender higher project efficiency and shorter project duration; however, the impact converged with increasing network density. The proposed model contributes to favorably observing the effect of social network aspects of project management and to efficiently estimating the efficiency and duration of construction projects.

Key Words: Collaboration, Project Management, Agent-based Modeling and Simulation, Social Network, Construction Process Simulation

1. Introduction

Construction projects tend to be massive, complex undertakings, and each is unique. Since the actions of one professional can have a significant impact on the concerns of the other, constructions cannot be completed by a single professional entity with a limited capacity and partial information [1,2]. The multidisciplinary functions for completing a construction also divide a project into many specialty contractors. Their communication during the entire project lifecycle is key to the success of a construction project. Collaborative practices among multidisciplinary people, who meet temporarily to execute a project, are required to accomplish common project objectives [1]. The importance of team efficiency resulted from the close collaboration among professionals during the entire project lifecycle to successfully execute large-scale construction projects has been emphasized in recent years [3].

Many essential approaches have been proposed to evaluate and increase the collaborative efficiency of project team members [4,5]. Regardless of the dynamic and uncertain manners of projects, many existing efforts concentrated only on the essential factors and qualitative

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measurement for evaluating the collaborative performance of a team [6,7]. Complementarily, event-driven computational models are widely applied to address fundamental and practical solutions in organization science by representing the stochastic and dynamic micro scenarios of the evaluated target [8,9]. Most of such models treat a company's employees, projects, products, customers, and partners as aggregated averaged quantities or as passive entities or resources in a process. Although these approaches can capture organizational dynamics and nonlinearity, they ignore the fact that all these entities have different histories, intentions, desires, properties, and relationships. Therefore, the social collaborations among team members, such as project information creation and sharing, in temporary teams cannot be easily modeled without a micro and dynamic viewpoint. Under this circumstance, the managers can just read the results from the computational model but the invisible problems behind the team members. To overcome this challenge, the agent-based modeling and simulation (ABMS) approach is frequently applied for representing and evaluating the behaviors of project team members because this approach is free from the limitations above as it suggests that modelers directly focus on individual objects in and around an organization, their behaviors, and interactions [10].

Moreover, the sociality of the project team is an essential but not-easy-captured feature for the computational model [12]. Project teams are regarded as information processing networks comprising members who are self-interest-seeking and myopic toward the recognition of entire communication networks [1]. For a construction project, informal social networks are team members' critical properties contributing their abilities to accomplish tasks quickly and to activate when unexpected problems arise [11].

Many computational models for evaluating project organizational performance following the concept of agent-based simulation (agent-based Simulation, ABS) were addressed [6,8,12,18]. These models provide an organizational-level team performance assessment framework, which developed a well-defined behavioral model for project performers and a mathematical model for calculating team efficiency based on time performance. However, the social network relationships of team members are not the primary focus of the researches. Therefore, not only the relationship between the team collaboration efficiency and the social network but also the collaboration bottleneck in the workflow arisen from the defects in the team social networks cannot be revealed due to insufficient analysis tools. In this circumstance, project managers can only try to improve the relationships of team members based on personal subjective and objective judgments which are risky the team collaboration efficiency could be decreased due to the subjective judgment errors.

Summarily, this study is eager to combine the ABMS with social networks to develop an agent-based project collaborative efficiency simulation model so that construction project teams can be considered complex systems composed of multi-professional people who are autonomous, goal-directed, and situated in an environment in which their aggregate behaviors emerge from the local interactions among them. Accordingly, not just an analysis model for evaluating the team performance but also an experimental tool for revealing the construction workflow bottlenecks resulted from the potential problems in the social networks of the project team is developed in this study.

2. Literature Review

2.1 Collaborative Efficiency Issues of Project Teams

Project management and enterprise organizational management literature richly highlight the importance of collaboration and efficiency issues in project team management. Easley et al. [14] presented a theoretical model in which usage of a collaborative system intervenes between teamwork quality and team performance for tasks that are supported by the cooperative system. Busi [7] found that there was a lack of understanding of what collaboration means and what it implied on the development of appropriate performance measurement systems.

Due to the naturals of complex and dynamics of the construction projects, the performance management for collaborative manners in the construction projects are still essential. Love et al. [15] described how change orders can impact the project management system, and using a case study and system dynamics approach to determine the major factors influencing a project's performance. Cheng et al. [16] proposed a team-based human resource planning method to deploy labor power for the workflows in a construction company. The relationship between manpower limitation and the project loading was observed by the simulation approach. Chang et al. [17] focused on the coordination issue to investigate coordination problems arising from design and construction concurrence and solutions by studying five ongoing design-build projects.

Moreover, scholars have found that the behavior of individual involved in the social networks of a project is relevant and essential for studying the collaboration performance of the project team [1,13]. Giri et al. [4] used the social network analysis (SNA) tool to analyze and map the interactions of individuals in the students' networks, and they found that regular meetings between students could be substantial for collaboration of students. Park et al. [13] showed a series of apparent tendencies in the development of collaborative networks to realize better profit performance under risky conditions for overseas construction projects; meanwhile, the study also validated the applicability of social network perspective in analyzing the collaboration in the construction domain.

2.2 Agent-based Modeling and Simulation for Project Teams

A new approach to modeling complex systems, ABMS, has its direct roots in complex adaptive systems. ABMS has recently become popular to investigate complex systems in many areas ranging from sociology, biology, and organizational study, to economics, business, and military studies. Unlike top-down modeling approaches, such as system dynamics and discrete event simulation, ABMS provides insight into the fundamentals of the process so that analysts could understand processes through which global patterns emerge [18].

ABMS has also adopted to evaluate the project efficiency in many studies. Jin and Levitt [6] developed the Virtual Design Team (VDT), a computational model of project organizations, to analyze how activity interdependencies raise coordination needs and how organization design and communication tools change team coordination capacity and project performance. After VDT model has been proposed, more advanced validations, applications, and modifications of VDT were addressed in the following decades [12,18]. Since the VDT model was not originally intended to capture cultural factors, Horii et al. [8] extended the VDT model to understand how cultural differences between Japanese and American firms in international joint venture projects affects team performance through computational experimentation. Although the large numbers of organizational and individual level behavioral parameters available in the VDT model can potentially represent cultural phenomena, the social factor is one of the essential perspectives for developing the next generation simulation model [12].

According to the discoveries of the previous research, we can determine both the computational analysis philosophy and the social network perspective are two essential methodologies for estimating the collaborative efficiency with dynamic manner. Summarily, following the methodology of ABMS, this study breaks the project team into individual agents and modeling the behaviors and the social network to simulate the collaborative interactions and performance.

3. Agent-based Project Team Collaborative Efficiency Simulation Model

3.1 Problem Statement

To understand how the social relationships of project team members affect the efficiency of a construction process, we are eager to design a simulation model for estimating the construction process efficiency of a project team considering the collaborative behaviors using agent-based modeling (ABM) and social network methodologies. Figure 1 demonstrates the boundary and the primary elements of the project team collaborative efficiency simulation (PTCES) model addressed in this paper. Since the project team members perform the construction process, the project team organization and the construction project network schedule, i.e., the construction process, are two fundamental elements in the real world we need to model. Based on the team organization structure of the project and the features of the construction process, first, we need to determine the required agents and their corresponding behaviors in the simulation model. Second, the social network is required to represent the collaborative relationships among team members. Third, the mathematical functions of the project team ef-

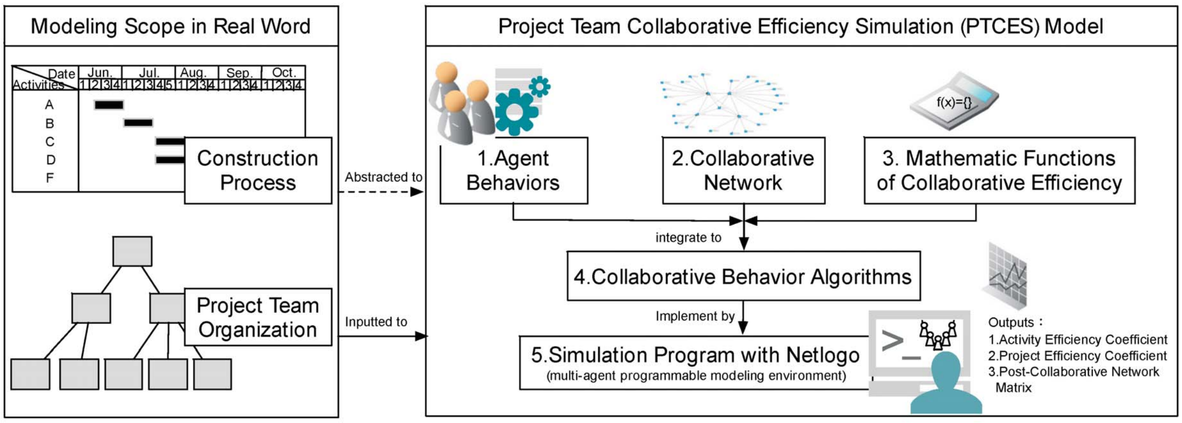


Figure 1. The modeling scope and the primary factors of the PTCES.

ficiency calculation are essential for estimating the individual and global efficiencies of the project. Then the algorithms for fulfilling the agents' behaviors and calculating the collaborative efficiency of the construction process in the simulation model can be developed. Finally, by using NetLogo [19], a multi-agent programmable platform, we can implement the generated model to be the experimental tool for estimating project efficiency.

3.2 Agent Behaviors of Project Team Collaboration

What the agents and what their corresponding behaviors are related with performing construction processes are the essential questions we need to answer for designing the PTCES. Figure 2 shows the agent breeds with their behaviors and workflow schemed based on the scope in Figure 1. One simulation will be started and stopped by the process agent with the process initializing and process management behaviors. The process agent will set up all activity agents and actor agents for initializing the process and then continuously manage the statuses of all activities for determining whether the process is completed. Once an activity is activated and assigned to its corresponding actor agent, the designated actor agent will perform the activity control behavior for commanding the activity agent starting to perform if no collaboration is necessary. However, if the actor agent lacks the required information or knowledge for completing the activity, the actor agent performs the collaboration to retrieve assistance from partners. The actor agent will collaborate with other agents via the collaborative network for ability exchange. If no partner in the collaborative network can provide necessary assistance, the designated actor agent will try to create new collaborative linkage, i.e., to discover a new friend, which will result in an extension of the collaborative network.

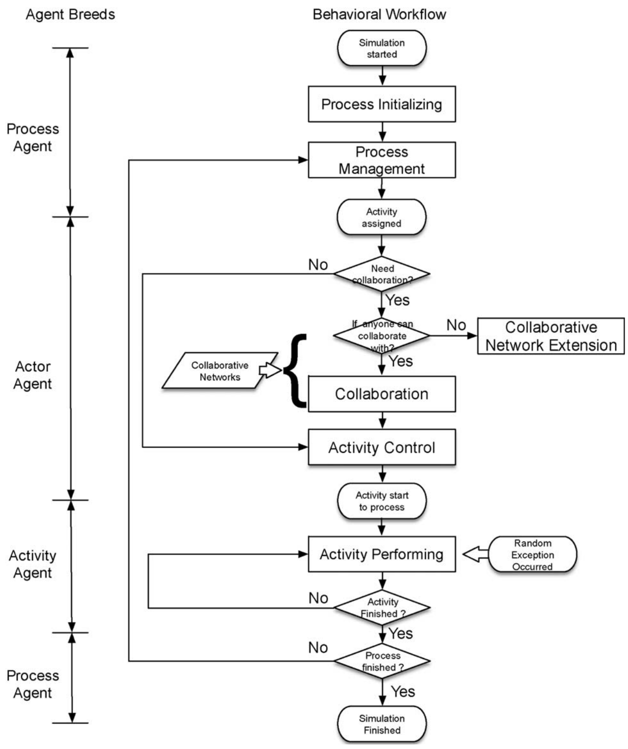


Figure 2. The agents and their corresponding behaviors in the PTCES (agent behavioral model of PTCES).

3.3 Mathematic Functions of Collaborative Efficiency

Following the collaborative behaviors, this study referred to the information-processing view of organizations in the VDT model [6,21,22] to calculate the efficiency of collaborations in construction processes. In the VDT model, a project team aims to complete the total amount of information-processing work; therefore, team members must retrieve the necessary information by communicating with other coworkers. On the basis of this concept, the following mathematical relations, proposed by Jin and Levitt [6], are applied as the foundation of this research.

For a given activity of a construction project, TW is the total work volume, which is the sum of the primary work volume (PW) and the collaboration work volume (CW), as shown in Eq. (1):

$$TW_i = PW_i + CW_i \tag{1}$$

where TW_i, PW_i, and CW_i are the corresponding *TW*, *PW*, and *CW* of activity *i*.

In addition, *PW* is the sum of the originally planned production work (*PWo*) and the production for rework (*PWr*) resulting from the failure of the original production work, as shown in Eq. (2):

$$PW_i = PWo_i + PWr_i \tag{2}$$

where PW_i, PWo_i, and PWr_i are the corresponding *PW*, *PWo*, and *PWr* of activity *i*.

From Eqs. (1) and (2), *TW* is the sum of *PWo*, *PWr*, and *CW* (Eq. (3)), and the spent time of *PW* is the sum of the processing times of *PWo*, *PWr*, and *CW* (Eq. (4)):

$$TW_i = PWo_i + PWr_i + CW_i \tag{3}$$

$$t_{TW_i} = t_{PWo_i} + t_{PWr_i} + t_{CW_i} \tag{4}$$

where t_{TWi}, t_{PWoi}, t_{PWri}, and t_{CWi} are the corresponding pressing times of *TW*, *PWo*, *PWr*, and *CW* of activity *i*.

For the construction activities of a project, *PWo* is given corresponding to the construction items in the contract, whereas (*PWr* + *CW*) varies depending on the activity properties and abilities of the team members.

According to Eq. (4), from a managerial viewpoint, the project team performs perfectly if the time of *TW* (t_{TW}) equals that of *PWo*(t_{PWo}). Therefore, the ratio (*EC*, efficiency coefficient) of t_{PWo} and t_{TW} indicates activity efficiency. As shown in Eq. (5), a lower EC implies the occurrence of a higher *PWr* time (t_{PWr}) or *CW* time (t_{CW}) during the project execution (and vice versa):

$$EC_i = \frac{t_{PWo_i}}{t_{TW_i}} \tag{5}$$

$$EC_p = \frac{\sum_{i=1}^{n} t_{PWo_i}}{\sum_{i=1}^{n} t_{TW_i}} \tag{6}$$

where EC_i ($0 \le EC_i \le 1$) represents the *EC* of activity *i* and EC_p ($0 \le EC_p \le 1$) represents the efficiency index of the entire project executed by the team members.

Because this study assumes that one communication task takes one unit time in the simulation model, the *CW* time spent by an actor for one activity depends on the total communication frequencies between the actor and his or her coworker.

To simulate this collaboration process, we continuously accumulate the *CW* time spent by actor A until actor B's willingness to collaborate with actor A (WoC_{AB}) is greater than the collaboration willingness threshold ($\hat{W}$). $\hat{W}$ is a global parameter in the simulation model, and this parameter represents the team members' minimum degree of ease of collaborating with one another. The higher the value of $\hat{W}$ is, the higher the possibility of the collaboration failing is. Although $\hat{W}$ varies among people, this study assumes that the project team members can have the same $\hat{W}$ value because their collaboration behaviors would become homogeneous since they might be influenced by the global culture of the project team. The team members' individual willingness of collaboration is assigned as a random value generated on the basis of the strengths of the relationships among them, as presented in Eq. (7). WoC_{AB} is randomly generated according to the Poisson distribution of the average strengths of S_{AB} and S_{BA}. If and only if WoC_{AB} is greater than $\hat{W}$, actor A collaborates with actor B.

$$WoC_{AB} = \left[x \sim poisson\left(\frac{S_{AB} + S_{BA}}{2} \right) \times 100 \right] \tag{7}$$

where *WoC* is actor *A*'s willingness to collaborate with actor *B*, *x* is a random Poisson distribution integer, S_{AB} is the strength of relation from actor *A* to actor *B* ($0 \le S_{AB} \le 1$), and S_{BA} is the strength of relation from actor *B* to actor *A* ($0 \le S_{BA} \le 1$).

In contrast to the *CW* time, the *PWo* time and *PWr* time can be calculated according to the actors' information processing speed and work volumes (*PWo* and *PWr*):

$$RPS_{ji} = [x \sim poisson(APS_{ji})] \tag{8}$$

$$t_{PWo(ij)} = \frac{PWo_i}{RPS_{ji}} \tag{9}$$

$$t_{PWr(ij)} = \sum_{t=1} \frac{PWo_i(t) + PWc_i(t)}{RPS_{ji}} \tag{10}$$

where RPS_{ji} is actor j's random processing speed for action i, APS_{ji} is actor j's average processing speed for action i, $t_{PWo(ij)}$ is the *PWo* time of activity i performed by actor j, $t_{PWr(ij)}$ is the *PWr* time of activity i performed by actor j, $PWo_i(t)$ is the primary production work volume of activity i at time t, and PWc_i is the correction production work volume of activity i as an exception occurring to activity i at time t.

On the basis of Eqs. (8), (9), and (10), the *PWo* and *PWr* times can be calculated according to actor j's *RPS*, which is randomly generated by the Poisson distribution function of actor j's *APS*. In this study, the values of the actors' *APS* must be surveyed with the project team members.

3.4 Primary Algorithms

To simulate the collaborative behaviors in the problem description, the three following fundamental algorithms based on the agents' behaviors in Figure 2 are addressed.

3.4.1 Collaboration Algorithm

When the actor agent is lack of the information or skills necessary to complete an activity, it must communicate with a supervisor or peer from its social network to obtain such information [22,23]. Specifically, the collaborative behavior can be modeled as a procedure of information/skill exchange (retrieving). The collaborative algorithm for information exchange is illustrated in Figure 3.

3.4.2 Collaborative Network Extension Algorithm

When an actor agent cannot retrieve the required information or obtain the necessary skilled assistance from the connected agent (friend), it must make new friends to extend its collaborative network and collaborate with them; or the actor agent cannot perform the assigned activity. According to the common-neighbor algorithm [20, 24,25], the actor agent determines the one not be in its ego social network which has the most common friends to be the potential friend, and asks if the agent is willing to create the friendship linkage with it. Once the potential friend agent rejected, the actor agent will randomly seek the other potential friend until new friendship linkage was created. Such a potential friend seeking algorithm is proposed as shown in Figure 4.

3.4.3 Activity Execution Algorithm

The activity execution behavior algorithm shapes the way how the activity agents perform the assigned activities. After performing the collaboration algorithm and the collaborative network extension algorithm, the actor agent (i) can activate the corresponding activity agent (ℓ) to execute the assigned activity. Based on the activity execution mechanism proposed by Levitt et al. [21] and the project team efficiency mathematical model described in

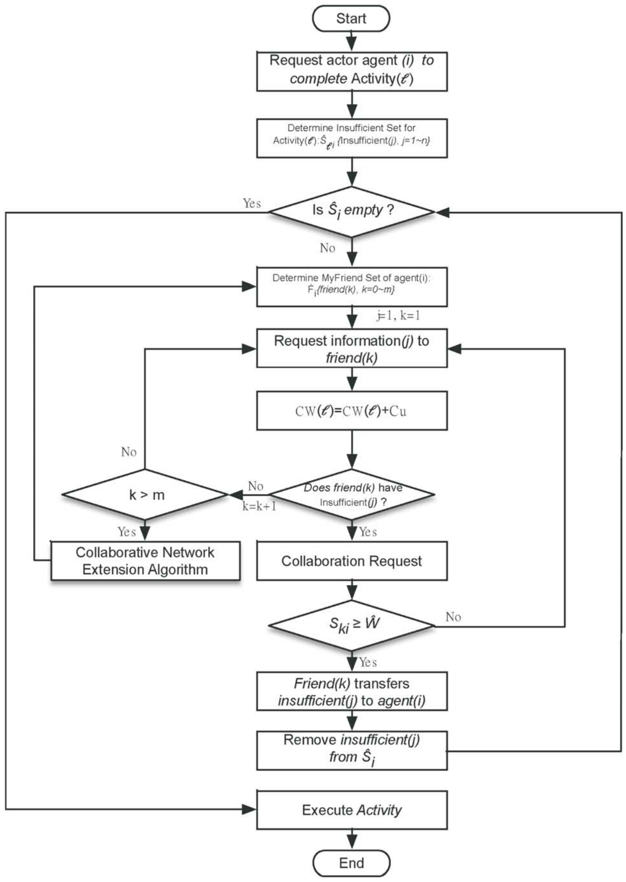


Figure 3. Collaboration algorithm of information exchange.

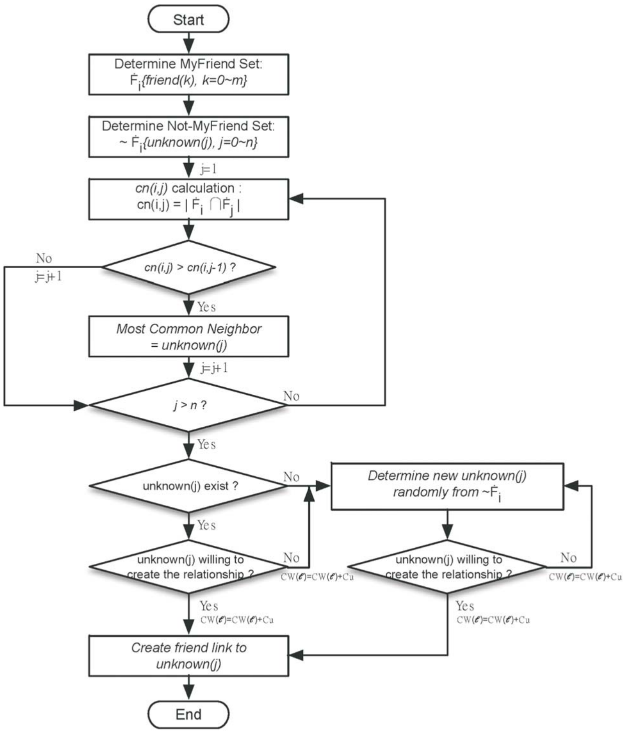


Figure 4. Collaborative network extension algorithm.

the problem statement, the activity execution algorithm for the activity agents is proposed, as illustrated in Figure 5.

To simulate the aforementioned activity execution behaviors stochastically, the essential probability parameters must be schemed. The exception probability (Pe, $0 \leq Pe \leq 1$) is used to check whether exceptions occur. If an exception occurs, the status of an activity agent (ℓ) is randomly set as Redo, Correction, or Ignore according to the rework probability (Pr, $0 \leq Pr \leq 1$) and correction probability (Pc, $0 \leq Pc \leq 1$). When activity agent (ℓ) requires a redo, the previous work time is accumulated as *PWr* time and activity agent (ℓ) must be restarted. As the correction exception occurs, an additional correction work volume is assigned to activity agent (ℓ) according to the correction ratio (Cr, $0 \leq Cr \leq 1$). The time to complete the correction work volume accumulates to the *PWr* time. The algorithm in Figure 5 is executed continuously until *PWo* of activity agent (ℓ) equals zero.

3.5 PTCES Implementation

Based on the aforementioned designed behaviors model, a multi-agent-based simulation development platform, Netlogo [26,27], is used to implement the PTCES. Figure 6 shows the main window of the simulation program. Four functional areas, namely, (1) setup, (2) simulation monitor, (3) command center, and (4) communication network, are included in the main window (Figure 6).

4. Case Study and Validation

4.1 Data Collection for the Study Case

To calibrate and validate the PTCES model, a real B2/9F building construction project was studied. The total cost of the project was approximately NT$15 million. The case study survey was enabled through the face-to-face interviews with project participants, which contained the in-depth interviews and collaborative questionnaires.

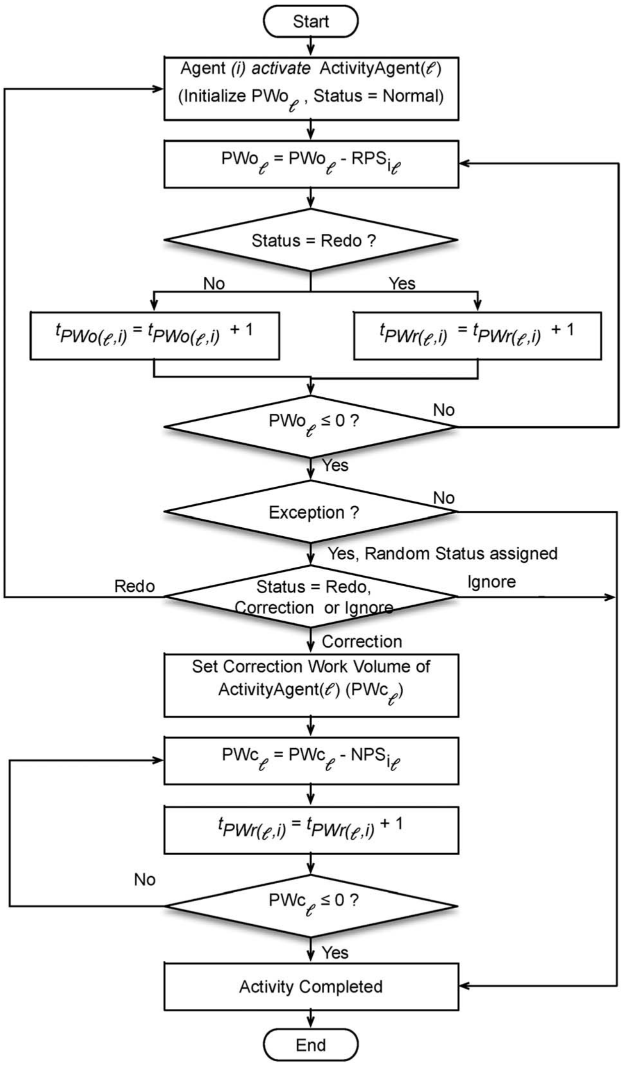


Figure 5. Activity execution algorithm of the activity agent (ℓ) activated by the actor agent (i).

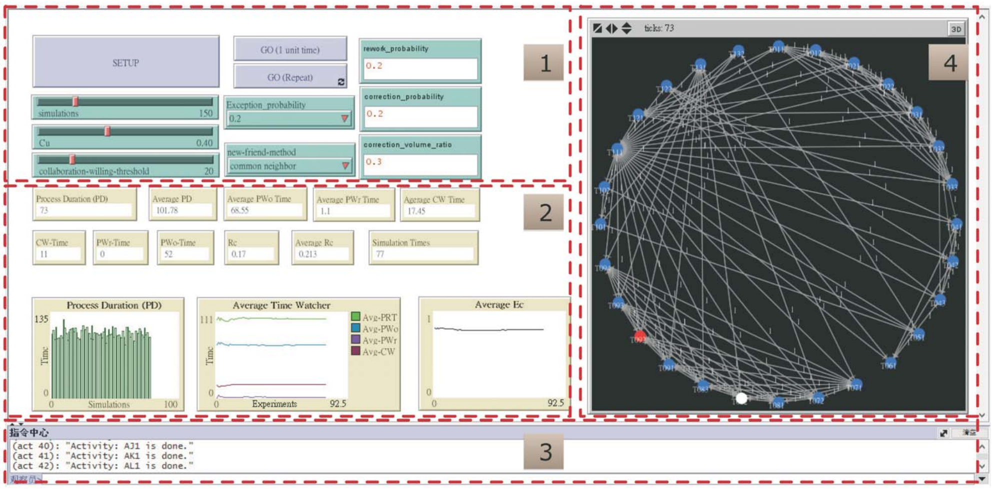


Figure 6. Main simulation window form of PTCES program developed using NetLogo.

The 15 project personnel provided by the study company were each notified of the survey and were given the opportunity to confidentially complete the survey. With the in-depth interviews, the bar chart schedule, organizational structure of the project, team member skills, and available information were collected. Table 1 presents 11 data sets of the structural building construction processes and the simulation results. The first data set was used to develop and calibrate the simulation model for the case project, whereas the other 10 data sets were used for validation. All activities along with their dependencies, durations, actors (subcontractors/trades), and production rates (i.e., *APS* as shown in Eq. (8)), in addition to the necessary skills/information were surveyed. Figure 7 demonstrates the schedule of the 23 activities in the first data set.

The team member data including the communication network matrix and actors' skills/information list were collected on the basis of the project organization structure and questionnaire interviews. Figure 8 shows the team structure related to the simulation processes in Table 1, whereas Figure 9 shows the communication network of the team members presented in Figure 8, indicating the formation of five cliques attributable to the division of trade by four different professional supervisors.

4.2 Simulation and Calibration

Adopting the performance of the case project as the baseline, we tuned the experimental parameters to calibrate the PTCES model to fit the baseline. The tunable parameters and their default values are outlined as follows: (1) exception probability (Pe = 20%), (2) rework

Table 1. Process datasets of the case study

Data set	Scope	Activities	Real duration (day)	Simulated duration (day)	Error
1 (calibration set)	Baseplate and B2 floor construction	23	76	76.75	
2 (validation set)	B1 floor construction	7	20	22.36	11.80%
3 (validation set)	1F structure construction	9	23	25.75	11.96%
4 (validation set)	2F structure construction	9	19	21.43	6.67%
5 (validation set)	3F structure construction	9	19	18.45	-2.89%
6 (validation set)	4F structure construction	9	19	19.32	1.68%
7 (validation set)	5F structure construction	9	19	17.74	-6.63%
8 (validation set)	6F structure construction	9	19	20.17	6.16%
9 (validation set)	7F structure construction	9	19	20.81	9.53%
10 (validation set)	8F structure construction	9	19	17.89	-5.84%
11 (validation set)	9F structure construction	9	19	19.44	2.32%

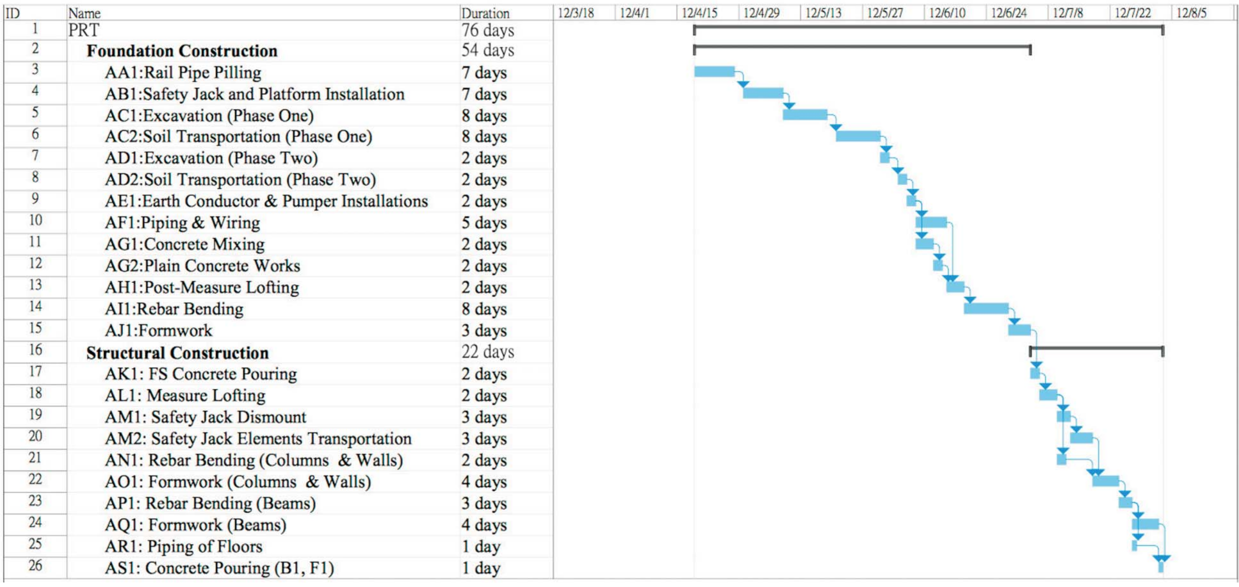


Figure 7. Actual timeline (bar chart) of baseplate and B2 floor construction of the case study.

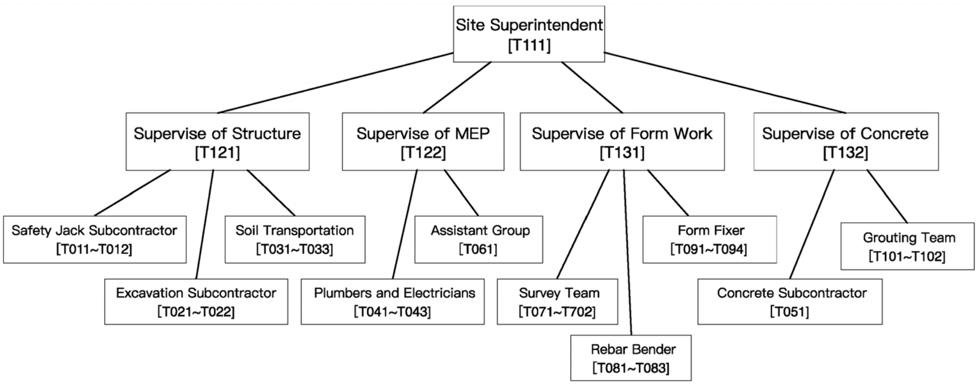


Figure 8. Team members of the processes in Table 1.

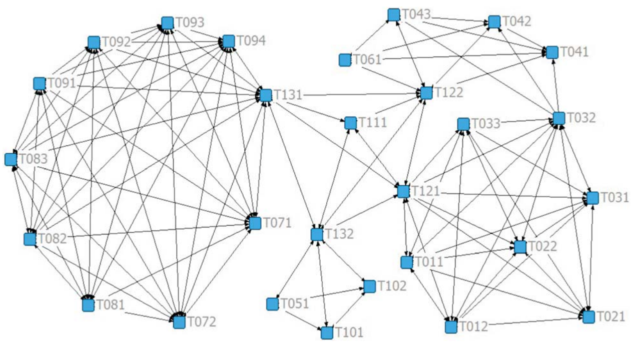


Figure 9. Communication network of team members in the case (density = 0.264).

probability (Pr = 20%), (3) failure for correction probability (Pc = 20%), (5) volume correction ratio (Cr = 30%), (5) collaboration willingness threshold ($\hat{W} = 0.1$), and (6) communication unit time (Cu = 0.4). Based on the above parameters' profiles, the calibration resulted in 76.75-day estimated process duration, 68.39-day PWo time, 0.96-day PWr time, 15.27-day CW time, and the average EC was 0.81. Because these estimations meet the results of the interviews with the project manager and staff, we applied these parameter settings to the following simulation experiments.

4.3 Verification

The statistical verification, including the discrete degree and the t-test approaches, is applied to ensure the soundness of the simulation model of the case study and the PTCES [28,29]. To understand the stability and variability of PTCES outputs, we first collected the simulation output data set of the additional 100 experiments. Subsequently, we applied several statistical techniques, such as means, standard deviations, and mean absolute deviations (MADs), to represent the variability of the PTCES model. Table 2 shows the standard deviation and MAD of each output value; because this table shows that they are relatively low, the stability of PTCES is acceptable.

4.4 Validation

On the basis of the collected data sets shown in Table 1, this study used the construction processes from B1 floor to the ninth floor to determine if the predictive results of the proposed model reflect the actual performance results of the project team. In Table 1, the predictive duration of each validation case is the mean value of 3 individual experiments involving a total of 900 simulations (i.e, each experiment includes 300 simulations). The errors ranged from approximately -6.63% to 11.96%. This comparison result shows the simulation model provides a referable estimation capability for the real cases.

5. Results and Discussion

5.1 Activity-based Analysis

The distribution of potential efficiency bottlenecks in a project process is essential information for enhancing project performance. The global efficiency of the entire construction process can reveal the result of only the work performed. By surveying the simulation results of all activities, which is microlevel information, managers can determine possible efficiency problems . Consider, for example, Figure 10; according to the *PWo* time, *PWr* time, *CW* time, and *EC* of the 23 activities within the baseplate and B2 floor construction process, the low-efficiency activities might be the potential efficiency bottlenecks of the simulated process. “AN1: Rebar Bending (Columns & Walls)” is the activity with the lowest efficiency (*EC* = 0.4) in this example; subcontractor T082 (rebar bender) spent 60% of the time on communication. A comparison of the initial and post-simulation ego communication networks of subcontractor T082 (Figure 11) indicates that subcontractor T082 created a new link to

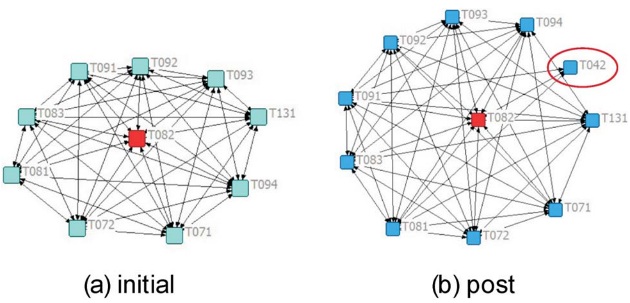


Figure 11. (a) Initial ego network and (b) post-simulation ego network of T082 (actor of activity AN1).

Table 2. Variability of PTCES outputs

	Project duration	Project PWo time	Project PWr time	Project CW time	Average project EC ($0 \leq EC \leq 1$)
Average	76.31 day	69.49 day	3.57 day	8.57 day	0.856
Standard deviation	1.06	0.88	0.61	0.39	0.993354
Mean absolute deviation	0.84	0.71	0.47	0.31	0.99

SD: standard deviation, MAD: mean absolute deviation.

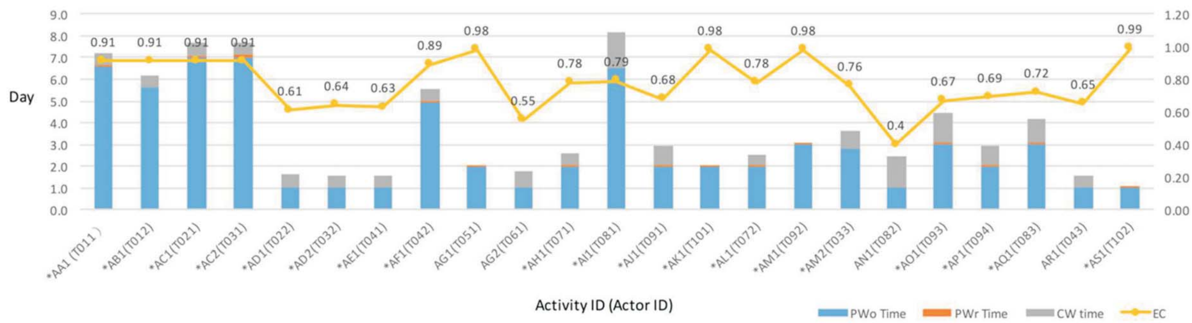


Figure 10. Time and EC distributions of each activity in the calibration data set of the case study.

subcontractor T042 (plumbers and electricians). In this case, subcontractor T042 is the missing link of subcontractor T082. Hence, if the site manager could have created a link between subcontractors T042 and T082 preliminarily, the duration of activity AN1 could have been shortened.

The process efficiency can be enhanced by complementing the missing links of the low-efficiency activities. Five subcontractors (T061, To91, T033 and T082) exhibited five missing links during the execution of their assigned activities. When the simulation was repeated using the new communication network without the missing links, the *EC* of the case construction process increased from 0.81 to 0.84, and the process duration shortened from 76.93 to 74.90 days.

5.2 Sensitivity Analysis

We used the sensitivity analysis approach to determine the effects of the parameters on the model and outputs in this study. Highly influential parameters of the project efficiency could be determined from the sensitivity analysis results. Figure 12 illustrates the estimated impact of each parameter on the collaborative efficiency of the project team (*EC*) (Figure 12(a)) and the project duration (Figure 12(b)). Figure 12 shows a linear adverse effect of each parameter on the *EC*, as arranged in the following order: $Cu > \hat{W} > Pr > Pc > Cr$. The parameter with the most significant impact is *Cu*. Consider, for example, *Cu* exhibiting an average slope of approximately -0.2321 (Figure 12(a)). In this case, with a 1% increase in *Cu*, EC drops by 0.2321% (and vice versa). Regarding project duration, the parameter with the most significant impact was $\hat{W}$, with the remaining parameters following the order $Pr > Pc > Cr > Cu$. Therefore, a higher parameter value results in longer project duration. For example, for a 1% increase in $\hat{W}$, the duration increases by 19.81%.

For both *EC* and project duration, $\hat{W}$ is a significant influencing factor, and it is modeled as a global parameter delineating the communication atmosphere of a project team [30]. A lower value of $\hat{W}$ implies more collaborations being encouraged in a project culture. Moreover, with a lower value of $\hat{W}$, information sharing and professional partnerships are expected to occur easily in the project team; the frequency of cooperation failure is also expected to decrease. Accordingly, the *CW* time of each activity decreases, resulting in project duration shortening and *EC* enhancement.

Compared with $\hat{W}$, *Cu* is more significant for project efficiency. However, the sensitivity analysis result illustrates the lowest influence of *Cu* on project duration. That is, if construction project managers attempt to shorten the project duration by relying on enhancing the collaborative efficiency of project teams, improving the communication atmosphere and eliminating collaboration barriers (decreasing the value of $\hat{W}$) would be a superior strategy to reducing the value of *Cu* by using advanced communication technologies. Developing the collaborative

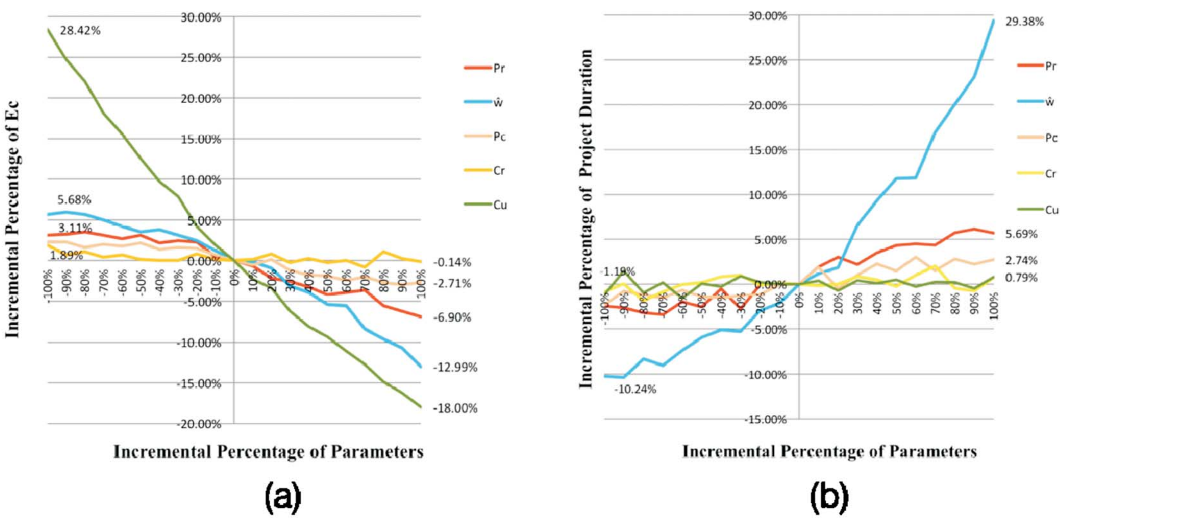


Figure 12. Sensitivity analysis for (a) EC and (b) project duration (total duration of the critical path of a construction project).

culture of a project team is essential for managing the project duration, rather than just decreasing the value of *Cu*.

5.3 Network Density Impact on Team Efficiency

As described in this section, we attempted to determine the primary manner in which the collaborative network affects project efficiency. Density, a basic social network measure to represent the trait of a social network [4], was used to observe the potential relation between it and the project efficiency.

Apart from the original collaborative network shown in Figure 9 (density = 0.264), the other two extreme collaborative networks (Figure 13) were experimented to estimate the potential range of project efficiency levels. Figure 13(a) illustrates a social collaborative network connected by only the formal organizational relationships, as shown in Figure 8; specifically, all trades and subcontractors do not know each other but their supervisors. Figure 13(b) presents a network with full connections (density = 1). Applying the three networks to simulate the same construction process in Figure 3, we observed that as the density increased from 0.095 to 0.264, the value of *EC* ranged from 0.68 to 0.878 (enhanced by 12.6%). The project duration was shortened from 97.52 to 78.11 days. Besides, the impact of density on project efficiency is nonlinear and weakens with increasing density.

6. Conclusions and Future Works

6.1 Conclusions

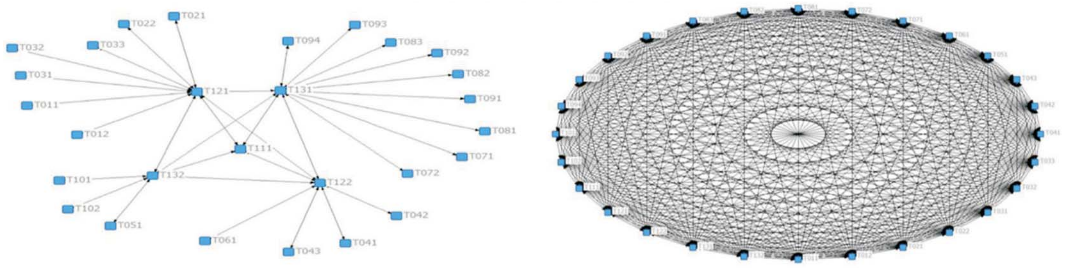
By adopting the agent-based modeling and simulation methodology, this study demonstrates the feasibility of the idea of using the social network to model the collaborative behaviors of the team members in a construction project. The PTCES model was addressed to be a computational tool providing the quantitative and objective estimations for construction project managers to understand the potential efficiency. We used a building structure construction project as a case study and verified the proposed PTCES model after calibration to ensure that could provide meaningful project efficiency and duration estimation information. The primary contributions are stated as follows:

6.1.1 Development and Benefit of PTCES

The PTCES model was schemed and implemented in this study so that we can quantitively estimate the project team efficiency considering the collaborative behaviors. The collaborative behaviors considering the social interactions were firstly addressed and implemented for the construction process by using agent-based modeling and simulation. Three primary algorithms, namely, collaboration, collaborative network extension, and activity execution algorithm, for performing the construction process were proposed in this study. Accordingly, we successfully implemented the PTCES with the NetLogo platform.

6.1.2 Limitation and Future Works

The results of the activity-based analysis using the PTCES illustrate the performance bottleneck resulted from the social network of the team can be discovered. Through the sensitivity analysis of the simulation experiments, two phenomena were observed: (a) developing a collaborative culture and reducing reworking risks are two dominant strategies for keeping a project on schedule, and (b) shortening the unit communication time can



(a) Density = 0.095 (b) Density = 1

Figure 13. (a) Communication network with only formal connections (mapped from the organizational relationships in Figure 8); (b) Communication network with full connections.

save project efficiency safely, but this may not reduce the project duration if the project team assumes an inappropriate collaborative culture. Finally, the characteristics of the social network, such as density, also influence projects. A high density (i.e., more connection ties) of the collaborative network was experimentally observed to increase project efficiency and shorten project duration; however, the impact converged with increasing density. Consequently, if creating relationships in a project team is costly, pursuing a high density of the social network of a project team can be an expensive decision for an organization.

6.2 Limitation and Future Works

In order to improve the soundness of the PTCES model, more case studies are required. For now, the PTCES has also been applied to estimate the collaborative efficiency of a building design team. Similar to the experience in this study, we found the PTCES can also provide referable estimation results for the multi-disciplining design team.

Although agent-based representations are easier to understand than mathematical representations of the same phenomenon, constructing the model out of individual objects, features, and rules for agents' movement of behavior is relatively severe. Not just only more observations are necessary to create the model, but also it is complicated to figure out the potential troubles during the simulation progress due to the complexity resulted from the implicit interactions of agents. This feature makes the agent-based model as a sandbox for engineers.

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