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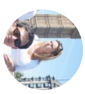

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Metanetwork Analysis for Project Task Assignment

Yongkui Li, Ph.D.[1]; Yujie Lu, Ph.D., A.M.ASCE[2]; Dongyu Li[3]; and Liang Ma, Ph.D.[4]

Abstract: Early studies of project planning endorsed a task-centric method, such as the program evaluation and review technique (PERT), that assigns relationships and tasks based upon the logical sequences of construction. This method works for projects with clearly assigned tasks, specific requirements, finely tuned organizations, and explicit roles and responsibilities for the project team. However, for projects that exist in a fast-paced and complex environment and are performed by temporary organizations, this task-centric method neglects the interdependence between project tasks and project contextual factors, such as project organizations, teams, knowledge, and resources that have considerable effect on task completion and project effectiveness. To investigate the congruence, the matching degree, between task assignment and the project's organizational environment, this study uses a three-dimensional metanetwork analysis (MNA) to model a project's personnel [hereinafter referred to as agents (A)], knowledge (K), tasks (T), and all six interconnected networks: AA, AK, AT, KK, KT, and TT networks. MNA can identify incapable agents and overloaded tasks, which hinder the completion of tasks, and then it can optimize task assignment to achieve better project performance. Cross-case comparative studies of 11 Chinese automobile dealership construction projects were conducted in order to validate the proposed MNA model and optimization strategies. During the project optimization, three key network-level measures—the congruence of agent knowledge needs (C_{OAK}), the congruence of task knowledge needs (C_{OTK}), and task completion based on knowledge (TC_K)—increased by 22.1, 24.6, and 47.3%, respectively. The results demonstrate that MNA can advance project task assignment theory to interactively analyze tasks and relevant organizational factors. Practical implications for diagnosing project organizations and task adjustments are also discussed at the end of the study. **DOI: 10.1061/(ASCE)CO.1943-7862.0001019.** © *2015 American Society of Civil Engineers.*

Author keywords: Meta-network analysis (MNA); Task assignment; Construction projects; Project network; Network analysis; Organizational issues.

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Introduction

Task scheduling is an essential part of project management. Based on a worldwide survey (Cooper 1994), many construction projects are unable to achieve their schedule objectives, most often because of inappropriate task assignment and scheduling. Poorly planned task scheduling could induce substantial schedule and cost overruns because it fails to exploit the true potential of a project system (Zafra-Cabeza et al. 2008). Traditional task-centric methods allocated project tasks according to their attributes, such as task-connecting sequences and workflow prerequisites (Chinowsky et al. 2010). The Gantt chart, for instance, exemplifies a classic task-scheduling method that uses bars to illustrate task duration and arrows to indicate the start-to-finish logical sequence among tasks. However, these methods neglect the interactions between the project tasks and other relevant project factors, and they are especially inadequate for projects that exist in open-ended environments in which the relations among project organizations, performance teams, professional knowledge, and multiskilled tasks are interconnected (Engwall 2003).

In such an interactive environment, the assignment of project tasks, including both the task sequences and the people who are expected to complete the tasks; the communication among the people; and the resources available to support the tasks need to be integrated so as to enhance performance and contribute to high-quality task completion. This is especially the case with complex projects that involve the integration of multiple ad hoc organizations. The traditional method of task allocation highlights numerous failures, such as schedule delays, cost overruns, and poor quality control. One way to address this issue is to use comprehensive, integrated, and interconnected information to plan the task scheduling. This calls for a strong effort to develop an innovative task-assignment system that incorporates task assignments with the relevant project elements, including organizations, knowledge, resources, and capabilities, in order to increase the efficiency and accuracy of task scheduling.

Recent studies have introduced social network analysis (SNA) to integrate project tasks with project organization and its social systems. The SNA provides the research opportunity and convenience to analyze interdependent organizational relations and structured behavioral patterns in a given project network. For example, Chinowsky et al. (2010) introduced a new SNA-enabled approach called project network interdependency alignment (PNIA) to assess project effectiveness by focusing on coordination, communication, and knowledge exchange across the project organizational network rather than using the traditional task-based approach. PNIA is a pioneer study, in which consideration of a project's social attributes significantly improved task scheduling and performance in a project-network environment. With the recent development of project complexity and multiperspective approaches to research problems,

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SNA, which was designed to model one dimension of social interactions, needs to be expanded to analyze the multiple interactions among organizations, agents, resources, knowledge, and tasks.

The MNA technique provides a promising way to understand the complex interactions in a project's organizational network. The metanetwork approach extends the analytical scope beyond one dimension and comprises a comprehensive project network that includes a variety of project elements and relations, such as information, tasks, knowledge, and resources. Equipped with multidimensional analytical perspectives and complex modeling capacities, MNA can precisely measure and diagnose project task performance, and thus help to optimize task scheduling and assignment (McCulloh and Carley 2008).

This study aims to measure and optimize the efficiency of project scheduling through the analysis of the metanetworks of projects and their related systems. To judge scheduling efficiency, the adaptability between project organizational abilities and task allocation is tested. The detailed objectives of this research are structured as follows: First, a metanetwork model will be established for a construction project, and the network measures to describe the congruence between project organizational abilities and task allocation will be identified. Then, the proposed model will be used to identify weak task assignments in the construction process and provide optimization suggestions to improve current practices. Last, the proposed model will be validated, the optimization approach will be tested with real construction cases, and some practical strategies to cope with inefficient project assignments will be suggested.

Literature Review

Task assignment intends to reasonably allocate tasks in work, in organizations, and in projects that will directly influence the work quality, organizational performance, and project success. The classic theory of task assignment was first established in the 1940s when operations research was developed and employed in the project management. Primary contributions include the Simplex method for linear programming, the Branch and Bound method for integer programming, and the Hungarian algorithm for the assignment problem (Kuhn 1955; Shih 1979).

Since the middle of the twentieth century, the engineering and construction industry has favored the continuing refinement of task-centered optimization approaches to evaluate the effectiveness of project task assignments. These approaches have included the program evaluation and review technique (PERT), task network scheduling analysis (Cottrell 1999), risk-based project scheduling and control (Ayyub and Haldar 1984; Zafra-Cabeza et al. 2008), design structure matrix to align sequential tasks with corresponding personnel (Browning 2001), and simulation-based task allocation and optimization (Lee 2005). However, as mentioned above, the traditional task-based project methods neglect the importance of a project's social environment and the complexity of human interactions, such as communication and knowledge exchanges across the project organizational network (Chinowsky et al. 2010), which can lead to inefficient scheduling results. Therefore, an increasing trend in schedule-improvement methods is to interrelate the project scheduling activities with the project organization, its behaviors, and its context.

Organizational Network, Project Task Assignment, and MNA

Social network analysis is a popular way to integrate task assignments with the roles of key individuals and their relations within project networks (Chinowsky et al. 2008; Chinowsky and Taylor 2012), and it aims to establish different human relations, formally and informally, within a project boundary in order to investigate and improve organizational efficiency. For instance, Chinowsky et al. (2010) established the relations between task allocation and the organizational network by combining SNA and task-network analysis. Taylor and Levitt (2005) explored the interorganizational knowledge flows in the project-based organizations, and Javernick-Will (2011) further described the interplay of relations between a project's organization and knowledge transmission in engineering and construction organizations (Javernick-Will and Scott 2010).

Social-network analysis has contributed greatly to the study of project organization and has achieved better performance in project task assignments in the following dimensions: (1) analyzing project networks from the perspective of leadership; (2) learning and development; (3) demonstrating that high-performing teams can be built through organizational learning, innovation, and the creation of a supportive organizational environment (Chinowsky and Taylor 2007); (4) examining the effectiveness of multinational organizations by transnational team network analysis (Schweiger et al. 2003); and (5) discussing and analyzing the key roles within a project network through actor-network theory (Blackburn 2002).

However, SNA for construction project networks is intended to address small networks, and only a few studies have considered extremely large networks. In addition, SNA usually consists of one type of node, such as agent networks or task networks. Even for multiple SNA, which may include different types of nodes, it also connects homogeneous nodes among one another. However, when assigning and scheduling project tasks, it requires both homogeneous and heterogeneous connections for various types of nodes, such as agent-knowledge, agent-task, and task-knowledge connections.

Thus, in order to evaluate the adaptability between task assignment and organizational capabilities, it is essential to extend the existing research boundary of SNA to multiple types of nodes and to more complex cross-connected project networks. Accomplishing this challenge demands a multidimensional network and advanced analytics and therefore drives the emergence and development of MNA.

The metanetwork theory provides a new way to address the above challenges. Metanetworks, which were first described as the precedence, commitment of resources, assignment, networks, and skills (PCANS) model (Krackhardt and Carley 1998), involve key entities that influence organizational design, such as tasks, resources, knowledge, and agents, as well as their relations (Carley 2002b). MNA, combined with mathematical calculation, can be employed to analyze different relations in a social network, such as friendship, family, and exchange relations. In MNA, any kinds of nodes in a project can be established and modeled, and such a rich modeling tool can significantly increase the efficiency and effectiveness of the project assignment. MNA has received extensive attention in many fields, such as dynamic networks for the integration of social networks and supply chains in the electronic-commerce market (Wakolbinger and Nagurney 2004), the integration of social and financial networks in electronic transactions (Nagurney et al. 2006), and the integration of a social network with a knowledge network (Nagurney and Dong 2005).

Comparison between MNA and Similar Methods in Task Assignment

Many simulation platforms, such as organization risk analysis (ORA) and Construct, have also been developed to address complex organizational issues, such as war strategies and international trade (Gerdes 2008; Moon 2008). Among various methods,

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it is worth mentioning that, much like MNA, the virtue design team (VDT) simulation system is also a computational model of project-organization-process simulation (R. E. Levitt, "Overview of the virtual design team (VDT): A computational model of project teams," working paper, Stanford University, California). VDT analyzes how activity interdependencies generate coordination needs and how organizational design and communication tools can change team coordination capacity and project performance (R. E. Levitt, "The virtual design team (VDT): A computational model of project teams," working paper, Stanford University, California). Although both the VDT-based and MNA-based models can characterize the organization in terms of agents, knowledge (expertise), tasks, and the relations among these, three striking differences exist between the two models.

First, the two methods have different goals. VDT is used to evaluate the design of teams doing routine work, while MNA is used to examine the ways in which organizations adapt to change (Carley 2002a). Therefore, the actors in MNA can adapt to changes and learn in the virtual experiments (Louie et al. 2003; Jin and Levitt 1996). Second, the assumption of connection for both models is different. VDT assigns each task (with a primary skill) to an actor, while MNA allows multiple actors and skills to link to a task (Louie et al. 2003). Third, different results are measured. One primary measure in VDT is the estimated duration of a project, which depends on the amount of work, reworks, the difficulty of the subtasks, and so on (Jin and Levitt 1996), while MNA specifically focuses on the accuracy of an organization in assigning the tasks by considering the congruence between organizational capability and task allocation (Louie et al. 2003).

MNA for Project Task Assignment and Project Organizations

MNA Concept, Elements, and Attributes

The metanetwork is a complex network composed of various entities and connections among them. It expands traditional organizational networks into multiple complex networks and is characterized by diverse project attributes and organizational contexts. The theory of metanetworks integrates a variety of research methods, including SNA, Link Analysis, and multiagent systems. With agents, knowledge, resources, and tasks involved, metanetworks can help extensively to analyze the dynamic evolution process of organizational change and its performance (McCulloh and Carley 2008). Key elements and relations may include project tasks, project team members and their knowledge, resources, geographic locations, etc. Metanetworks can be simply expressed by the metamatrix, which describes the nodes and their connecting links. Table 1 presents a sample of a metamatrix, which includes agents, knowledge, and tasks.

For analyzing project assignments, the metanetwork possesses two unique attributes that are different from other network analysis methods such as SNA. First, the metanetwork is a dynamic system that can adapt to organizational change. When the project objective changes, the nodes in the network, including agents, knowledge, resources, and tasks, will change accordingly to help achieve the new objective. Similarly, the links between any two nodes can be restructured, revised, or removed (Carley 2002a). All of these changes trigger the evolution of a subnetwork, or even a whole new metanetwork. For example, once a small change occurs in the knowledge-task (KT) network, the agent-task (AT) network and agent-knowledge (AK) network will have ripple effects.

Second, the metanetwork is a complex system in both its structure and connection diversity. The structure of the metanetwork is established to show almost every dimension of a project organization by using multiple types of nodes and enormously detailed nodes. In addition, the network connections among different nodes can measure both the importance and direction of the connecting link. For example, in the AK network, an agent could possess different proficiencies based on the related knowledge, and such differences can be reflected as the weights of those links. Meanwhile, connections could be either one way, such as a task sequence or order instructions, or two way, such as information exchange or organizational coalitions. The pluralities of both network nodes and connections elevate the complexity of the system exponentially and make the effects of a metanetwork far beyond the capacity of conventional organizational network analysis.

A construction project organizational network, which has many dynamic and complex characteristics, is an appropriate example of a metanetwork. In the construction practices, numerous project participants and stakeholders frequently interact with one another to pursue a common project objective, showing complex network relations. Meanwhile, the continuous emergence of new professional knowledge and technical proficiencies, as well as additional or restructured organizations, is common in the construction process and requires dynamic project change. Therefore, it is necessary and essential to use MNA for studying the project task assignment in terms of its dynamic, complexity-oriented, and multiperspective analytical features. The following is an exploration of conceptual models of MNA in construction projects.

Developing the MNA Model

The construction project metanetwork model can be established in two steps: (1) determining key entities and (2) linking these entities. The first step is to identify key entities that affect the project scheduling performance. This study selects three key entities to establish the metanetwork conceptual model as follows.

First, tasks are identified as key entities since the construction industry evaluates projects based on the completion of tasks. Then

Table 1. Structure of MNA Network and Its Elements

		Node class and interpretation		
Node class	Explanation	A (agents)	K (knowledge)	T (tasks)
A (agents)	Tie	AA/interaction network	AK/knowledge network	AT/assignment network
	Phenomenon	Who knows who	Who knows what	Who is assigned to what
	Dynamic	Structure redesign	Learning	Re-tasking
K (knowledge)	Tie	—	KK/information network	KT/knowledge requirements network
	Phenomenon	—	What informs what	What knowledge is needed
	Dynamic	—	Innovation	Training
T (tasks)	Tie	—	—	TT/precedence network
	Phenomenon	—	—	What needs to be done before
	Dynamic	—	—	Process planning

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the project team (also called the agent) that performs all of the tasks is identified as another entity. In addition, both the interorganizational and cross-organizational exchange of knowledge and information influence greatly the effectiveness of the task allocation (Alavi and Leidner 2001; Brown and Duguid 1991), and so they are considered together as another entity. Among these three entities, *agents* are the engineering or construction firms or their key personnel, *knowledge* is deemed to be the capabilities or skills mastered by agents, and *tasks* are all of the engineering or construction activities performed.

The next step is to establish connections between the entities. The AT network connects the agents and tasks, the AK network links agents and their knowledge, and the KT network connects tasks and their required knowledge. In addition, the AA, KK, and TT networks, which reflect the links among the nodes of the same entity, can also be established. The above six networks construct a conceptual metanetwork model for construction projects.

Quantitative Measures for Project Task Assignment and Project Organizations

The metanetwork can be analyzed by a series ofquantitative measures in two categories: network-level measures and node-level measures. The former characterize the entire network or a subnetwork, and the latter describe the features of a single node. After reviewing past studies, this study selected six measures to quantify the congruence between the project task assignment and the organizational capabilities. These six measures were found to be the most cited and widely validated measures in many studies (K. Carley, "Summary of key network measures for characterizing organizational architectures," working paper, Carnegie Mellon University, Pittsburgh, Pennsylvania; Lanham et al. 2011; Lee and Carley 2004), and therefore they can be assumed as reliable indicators in this study.

Three node-level measures are (1) the congruence (the matching degree) of agent knowledge needs C_{AK} (i), (2) the congruence of task knowledge needs C_{TK} (i), and (3) the actual workload based on knowledge AW_K (i). The three network-level measures are (1) the network-level congruence of agent knowledge needs C_{OAK}; (2) the network-level congruence of task knowledge needs C_{OTK}; and (3) the network-level task completion based on the knowledge TC_K, which is used to measure the adaptability between project task assignments and the organizational capabilities. The detailed definitions, notations, and calculation formulas of these measurements are shown in Fig. 1. The C_{AK} (i), C_{TK} (i), C_{OAK}, and C_{OTK} have been slightly modified from the original calculations in

Measure Name	Description	Formula
Node-level Congruence, Agent Knowledge Needs (C_{AK}(i)) (J. Lee & Carley, 2004)	The amount of knowledge that an agent owns to complete its assigned tasks expressed as a percentage of the total knowledge required for the assigned tasks.	$C_{AK}(i) = 1 - C_{AK}(i)^*$ $C_{AK}(i)^* = \frac{\sum_{j=1}^{\lvert K\rvert} N_{i,j}(\sim AK_{i,j})}{\sum_{j=1}^{\lvert K\rvert} N_{i,j}}$ Let N = AT*KT'
Node-level Congruence, Task Knowledge Needs (C_{TK}(i)) (J. Lee & Carley, 2004)	The amount of knowledge supplied to complete a task expressed as a percentage of the total knowledge required for the task.	$C_{TK}(i) = 1 - C_{TK}(i)^*$ $C_{TK}(i)^* = \frac{\sum_{j=1}^{\lvert K\rvert} KT^{t}_{i,j} * (S_{i,j} = 0)}{\sum_{j=1}^{\lvert K\rvert} (KT)}$ Let S = AT'*AK
Node-level Actual Workload, Knowledge Based (AW_K(i)) (K. Carley, 2002)	The knowledge an agent uses to perform the tasks to which it is assigned. Individuals or organizations that are high in workload are those who complete more complex tasks and also have the knowledge to do those tasks.	$AW_K(i) = \frac{AK * KT * AT'(i,j)}{sum(KT)}$
Network-level Congruence, Organizational Agent Knowledge Needs (C_{OAK}) (J. Lee & Carley, 2004)	Across all agents, the knowledge that agents own to do their assigned tasks expressed as a percentage of the total knowledge needed by all agents.	$C_{OAK} = 1 - C_{OAK}^*$ $C_{OAK}^* = \frac{\sum_{i=1}^{\lvert A\rvert}\sum_{j=1}^{\lvert K\rvert} N_{i,j} * (\sim AK_{i,j})}{sum(N)}$
Network-level Congruence, Organizational Task Knowledge Needs (C_{OTK}) (J. Lee & Carley, 2004)	Across all tasks, the knowledge supplied to complete them expressed as a percentage of the total resources needed by all tasks.	$C_{OTK} = 1 - C_{OTK}^*$ $C_{OAK}^* = \frac{\sum_{i=1}^{\lvert A\rvert}\sum_{j=1}^{\lvert K\rvert} N_{i,j} * (\sim AK_{i,j})}{sum(N)}$
Network-level Task Completion, Knowledge Based (TC_K) (K. Carley, 2002)	The percentage of tasks that can be completed by the agents assigned to them, based solely on whether the agents have the requisite knowledge to do the tasks.	let Need = (AT'*AK) - KT' let $F = \{i \mid 1 \le i \le \lvert T\rvert, \exists j : Need(i,j) < 0\}$ $TC_K = \frac{\lvert T\rvert - \lvert F\rvert}{\lvert T\rvert}$

Note: The formulas with the *symbol (C_{AK} (i) *, C_{TK} (i)*, C_{OAK} (i)* and C_{OTK} (i)*) are the original calculations.

Fig. 1. Six measures for the congruence among project organizational agents, tasks, and knowledge

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order to show positive correlations among all measures and organizational attributes. The specific approach is to use 1 minus the original value, which has a range of 0–1. For example, C_{TK} (i)* initially indicates the proportion of the deficient knowledge as part of the total knowledge required for the task (Lee and Carley 2004), but after modification the new value C_{TK} (i) indicates the proportion of the total knowledge required that the agent possesses.

Calculating and Optimizing MNA Results

To calculate the MNA result for each project, the project data are required to be collected and tabulated into the calculating formulas in Fig. 1. After calculating and validating the measures, the project metanetwork can be analyzed based on three entities—agents, knowledge, and tasks—and six types of networks—AA, AK, AT, KK, KT, and TT networks. This analysis is intended to identify weak nodes or links in the metanetwork and then enable the network optimization to improve the overall network performance.

The optimization is conducted according to the following protocol: (1) After identifying weak nodes (or links) in the previous analysis, the study will examine all relevant factors to locate weak nodes or links that have the potential to be improved. For instance, if an agent is identified as having insufficient knowledge, then the agent's role in the network, the agent's task-completion ratio, and practical barriers should be examined. (2) The matching principle among nodes or links with a potential for improvement and the project's realistic situation needs to be considered. For instance, in the AT network, it must be determined whether it is practical to reassign the tasks in a short time. (3) The overall network performance measures, task completion based on the knowledge (TC_K) in particular, are used to monitor the network performance during the optimization process. In order to verify this method and demonstrate its practical application, the following sections will conduct the cross-case comparative studies of 11 general motors (GM) Buick automobile dealership new construction projects in China.

Case Study

Case Background

A 4 S dealership provides full services for an automobile brand, including car sales, spare-parts sales, after-sale service, and surveys. A 4 S franchise dealership is typically required to be built by following corporate identity (CI) to highlight the brand value. As a result, the firms involved in the construction of 4 S dealerships (or called shops) commit to completing a series of tasks based on the brand's requirements, such as design standards, procurement requirements, and a quality-assurance system.

The construction of the Shanghai Buick 4 S dealership was selected as the case that would be studied. Each year, about 70 new Buick 4 S dealerships are constructed in China, and the construction cycle of a project usually lasts for approximately 175 days. Buick enters into 4 S dealership contracts with local business partners (hereinafter called local dealers) and grants the 4 S franchise to them. The local dealer, as the project owner, has overall responsibility for the construction and operation of the 4 S shops in accordance with Buick's CI requirements. Because of the large number of local dealers who have different qualifications and capabilities in managing construction projects, there can be significant variances in the final performance of 4 S construction projects. Our case study, which has similar tasks but different performers, aims to analyze how differences in task assignments affect project performance.

In order to effectively oversee the performance for all local 4 S shop construction, Buick invites project management consultants (PMC) to manage and supervise the entire design and construction process for all local projects. For each project, PMC will perform four on-site inspection visits, namely field survey and measurement (PM1), technical disclosure and coordination (PM2), mid-term examination (PM3), and preacceptance visit (PM4). At the completion of PM4, PMC will produce a project preacceptance evaluation report to reflect the actual project performance in terms of its quality, cost, time, and so on. This report is recognized by Buick as a critical benchmark to assess the project performance and also used as the same purpose in this research.

As shown in Fig. 2, the case study is performed in three steps. The first step is to build the project metanetwork model by identifying the nodes and links in the project. The second step is to calculate the model results of the proposed six measures and validate the model by examining the correlation among the six measures and the project's actual completion performance. The third step is to examine a poorly performed project to identify inappropriate task assignments and then to modify the knowledge and assignment networks accordingly. The following sections will elaborate on each of these three steps.

Data Collection and Model Establishment

The data used in the case study were collected from 11 real projects constructed in 2012–2013 in China. The authors worked closely with the PMC during the two years of data collection and were given full access to project-relevant archives and documents, which included project management and construction management manuals, the dealers' annual reports and official websites, PMC service checklists, PMC onsite work-inspection reports, project preacceptance evaluation reports, etc. In addition, the authors also conducted site observations and several rounds of interviews with project participants to facilitate the case development process. The structured information table was designed to collect basic information from PMC team members, local dealers, designers, and contractors. The asked questions included their qualifications, educational degree, experience with similar projects, working years, etc. In addition, the semistructured interviews were conducted for all project participants to specifically collect information for *who possesses what knowledge* in the AK network and *what knowledge is required for a task* in the KT network. Those exclusive project experiences and multiple sources of evidence provide triangulation for the case analysis, improving the reliability and validity of the case results.

Identifying Nodes

This study selected three entities: main project participants as the agents (A), individuals with professional knowledge of project management (K), and all of the tasks (T) required to accomplish a project.

For the entity of agents, main participants of the project are identified. One agent node can represent either a person or an organization. Each node is a minimal functional unit which can independently perform its role, make major decisions, and take responsibility in a project. For example, the PM Director (A02) is a node because it has a leading position within an organization and assumes tasks individually. A structure contractor (A040201) is also considered a node because it works as a team to deliver the structural component of a 4 S store. In total, 12 main participants were selected as the agents—1 from the owner, 3 from the PMC consulting team, 3 from the suppliers, and the others from local stakeholders.

For the entity of knowledge, 16 kinds of knowledge for project organization and project management were identified and used in accordance with the similar category described in the PMBOK and OmniClass, including planning, design, project management, site surveying, construction, supplying, and decision making. For project

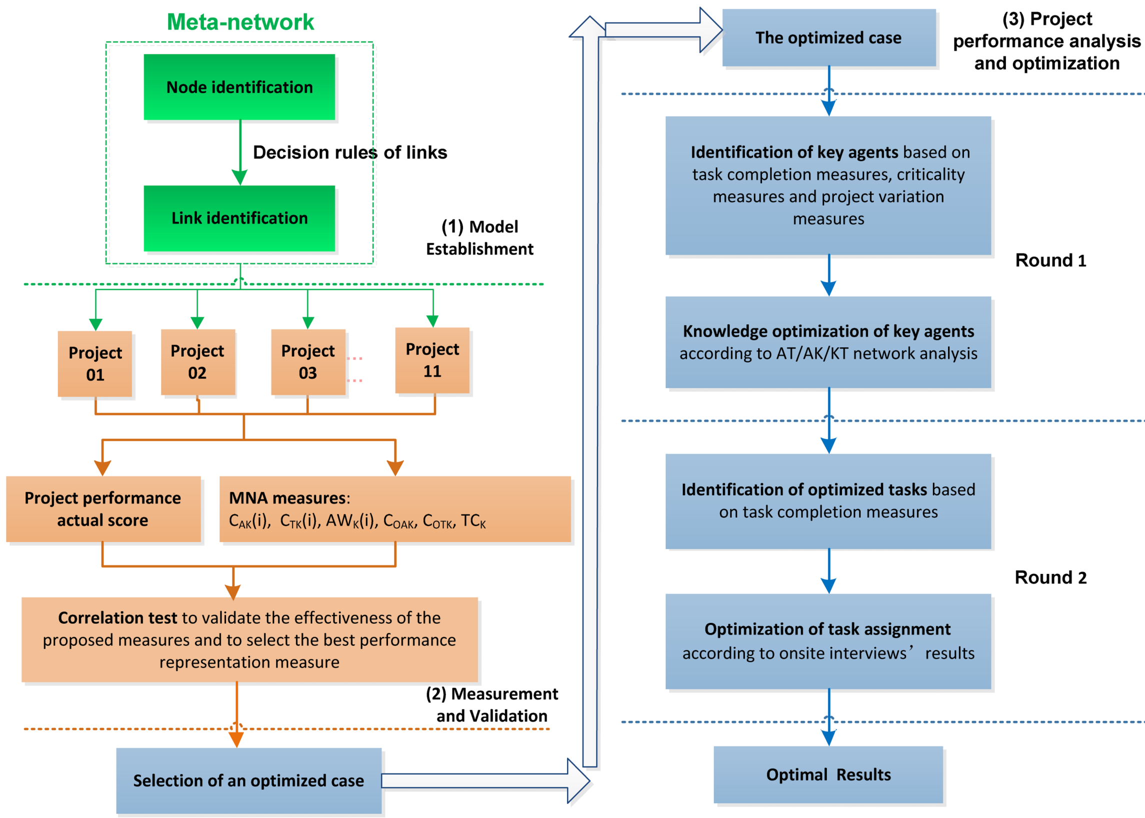

Fig. 2. Sequence of the case study

management knowledge, it can be further divided into scheduling, contract administration, procurement management, quality control, and cost control. For design knowledge and construction knowledge, they can be categorized into different levels (normal, 4 S shop, outstanding) based on the nationally regulated qualifications and previous experiences of designing or constructing 4 S shops. In addition, 64 tasks which cover the process of design, construction, and project management were determined according to the construction management manual of Buick projects.

Connecting Nodes

Each node is connected with others from the same or different entities. Any two styles of nodes and their connections (also called links) comprise a network or subnetwork. In this case, six types of networks are formed: AA network, KK network, TT network, AK network, AT network, and KT network. Four out of the six networks have been widely used in construction research and practice. Traditional SNA focuses on the AA network to examine the interactions among agents. Both AT and TT networks are common planning tools used in construction engineering organizations, where the AT network can be described as the responsibility-assignment matrix and the TT network is the task-scheduling chart. The KK network considers the similarities and substitutable relations among different types of knowledge (Nagurney and Dong 2005). These networks retain the standardized and unified elements from the classic project management theory and remain similar in most project models.

The AK and KT networks refer to an agent's knowledge requirements and a task's knowledge requirements, respectively. The former represents *who knows what*, and the latter means *what knowledge is needed for a particular task*. Currently, few studies in the field of construction management exist that explore the relations between these two networks. This study uses the network rule that is based on previous research (K. Carley, "Summary of key network measures for characterizing organizational architectures," working paper, Carnegie Mellon University, Pittsburgh, Pennsylvania), which includes the attributes of knowledge, tasks, and agents from the construction industry, as well as the real case background.

For the AK network, we conducted semistructured interviews with Buick managers, PMC team members, local dealers, and so on to determine the rules for an agent and its associated knowledge. For example, the level of construction knowledge of structure contractors (A040201) is determined by its national certified contractor qualification and previous experience of building 4 S shops. The contractor who has not obtained the secondary national qualification (level II) for *general contractor for housing construction* or obtained level II but without previous construction experience for 4 S shops was rated *normal* construction knowledge (K0501); the contractor who has obtained the level II qualification and owned previous construction experience for 4 S shops was rated *4 S shop* construction knowledge (K0502); and the contractor who has obtained the highest qualification (level I) *general contractor for housing construction* was rated *outstanding* construction knowledge (K0501). All interviewed results were tabulated to form the connections in the AK network.

KT network describes the relationship between a task and its associated knowledge. For most tasks, their knowledge requirements can be easily determined based on the task description written in the construction project management manual. However, several tasks are professional and they require special expertise to be understood. Therefore, the semistructured interviews with onsite engineers were carried out to affirm the required knowledge of these tasks by asking questions, such as, "What expertise or experience is most needed in performing this task?" and "Is any additional knowledge required for this task?"

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Knowledge, as a special type of project resource, has typical *specificity* or contextual relevance across projects (Cramton 2001). The same tasks in different projects may require different knowledge sets. In this case, three such special tasks were identified, namely T0213 (interior decoration works), T0222 (interior surface finishes), and T0303 (rectification and completion). The reason is that their knowledge requirements are closely affected by the results of previous PMC on-site inspections. Different PMC inspection results may trigger various knowledge requirements to complete the subsequent tasks. Specifically, an unsatisfactory previous inspection result requires a higher level of knowledge to complete subsequent tasks.

Therefore, these three special tasks require special knowledge. According to the experiences of interviewees, this study uses the following rule to operationalize different requirements. If there is no schedule delay and less than five construction rectifications are ordered in one on-site inspection visit, the subsequent task can be completed by the contractor with standard 4 S shop-construction knowledge (K0502). If an inspection visit identifies project schedule delays or finds more than five required constructive rectifications, the subsequent task has to be completed by a contractor with outstanding construction knowledge (K0503).

The strength of a connection is evaluated by a binary system in which *connected* is represented as 1 and *not connected* is represented as 0. One exception is the KK network connections, where the learning scale of the knowledge is divided into three levels based on engineers' working experience, specifically 1 for outstanding knowledge, 0.8 for 4 S shop knowledge, and 0.5 for standard-level knowledge.

Modeling Tool

After identifying all nodes and their connections in the model, this study employs the *Organization Risk Analysis (ORA) NetScenes* 3.0.0.2 software program for calculation. The ORA platform, which was developed by Carnegie Mellon University, is a mainstream simulation tool for the application of metanetwork theory (Carley and Reminga 2004). Based on metanetwork analysis, ORA is a network analysis tool that detects risks or vulnerabilities in an organization's design structure. For detailed information about this platform, see the ORA user's guide (Carley and Reminga 2004). The use of ORA has already been validated in other industries (Effken et al. 2011), but this research is the first to use it for examining construction organizations.

Measurement and Validation of the Model

Table 2 shows the results, after calculation, for the 11 projects in terms of six proposed measures. Among these projects, P10 and P11 rank the highest for most of measures while P01 and P07 performed the worst.

To validate the effectiveness of the proposed model and measures, this study compares the correlation among the six selected measures and the actual project performance. Buick asks the PMC to monitor projects in four visits as described above, and the PMC will holistically evaluate the project's total performance and report the scoring result in a project preacceptance evaluation report after PM4. The evaluating scores can objectively reflect the actual performance of the project in its quality, cost, and time. Therefore, these actual scores (Table 2) are selected as the benchmark for project performance, with which the other six measures are compared.

As shown in Table 2, the correlation results support the proposition that all selected MNA measures are positively correlated with the project's actual score. The correlation coefficients range from 0.799 to 0.945, with a significance level (p value) less than 0.05. This indicates that the six measures can largely represent the actual performance of the project and be used as validated measures to forecast project performance.

Among these measures, *task completion based on the knowledge* (TC_K) has the highest correlation (0.945) with the actual project score, and it is highly correlated with other measures (Table 2). Therefore TC_K was selected as the best indicator to represent overall project performance in the next optimization step. This could be explained by the definition of six measures as well. For three node-level measures, the project performance was evaluated by averaging values for all project nodes. This method does not consider positions, weights, and importance of different nodes, so it cannot represent the true project performance. For the other

Table 2. Results of the MNA Measures and Actual Scores for 11 Projects

Measures	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	Minimum/maximum value and associated nodes for the P01
C_{AK}	0.650	0.727	0.668	0.731	0.707	0.664	0.649	0.701	0.710	**0.747**	**0.735**	Min = 0.106; A04 (the local dealer) Max = 1; A0301, A0302 and A0303
C_{KT}	0.684	0.729	0.748	0.804	0.807	0.789	0.688	0.801	0.786	**0.813**	**0.808**	Min = 0; 17 nodes (26% of total nodes) Max = 1; 38 nodes (59% of total nodes)
AW_K	0.064	**0.077**	0.064	0.074	0.073	0.070	0.065	0.074	0.070	**0.075**	0.074	Min = 0.007; A040201 (the main structure contractor) Max = 0.257; A0202 (the project manager)
C_{OAK}	0.529	**0.637**	0.529	0.608	0.602	0.577	0.537	0.608	0.582	**0.622**	0.617	N/A
C_{OTK}	0.671	0.743	0.686	0.771	0.770	0.734	0.676	0.771	0.741	**0.784**	**0.777**	N/A
TC_K	0.594	0.719	0.656	0.719	**0.75**	0.703	0.594	0.734	0.734	**0.766**	**0.75**	N/A
Actual project score given by the PM												
Score	87	109	99	103	**119**	107	84	110	110	118	**119**	N/A

Note: For the node-class measure, the number is for the average values of all the nodes. For each measure, the two lowest values are underlined and the two highest values are bold. Correlation analysis among the above measures and the actual scores is as follows: The actual project score is highly correlated with C_{AK} (correlation coefficient 0.799), C_{TK} (0.871), AW_K (0.792), C_{OAK} (0.809), C_{OTK} (0.896), and TC_K (0.945). TC_K is also highly correlated with C_{AK} (0.870), C_{TK} (0.918), AW_K (0.871), C_{OAK} (0.873), and C_{OTK} (0.961). All the statistical results are proved by t-test (p value < 0.05).

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two network-level measures, *the congruence of agent knowledge needs* (C_{OAK}) evaluated the project network from the perspective of agents, while *the congruence of task knowledge needs* (C_{OTK}) assessed the network from the perspective of tasks. Both of them only assess the performance from a certain perspective, and therefore they do not reflect a holistic view of project performance.

Project Performance Analysis and Optimization

When comparing the results of measures among different projects, the study found that 11 projects performed in a significantly different way. The best-performing project (P10) is 22.5% higher in *task completion based on the knowledge* (TC_K) than the worst-performing ones (P01 and P07). Given that all projects shared similar task assignments and resources, such varying performances suggest that certain projects may present inappropriate congruence between agent's knowledge and task assignment. To further analyze the reasons and explore possible paths to optimize the underperformed projects, this research selected an extreme case which has the lowest performance for the optimization as follows.

Identify the Optimized Project

Among the 11 cases, the project in Anyang (P01) is determined as the optimized case because it had the lowest TC_K value (0.594) and the second lowest actual project performance score (87; Table 2).

With regard to the network-level measures of P01, the value of TC_K is only 0.594 (see column P01 in Table 2). Such poor performance can be explained by two possible factors: (1) the agent possesses an insufficient level of required knowledge to complete the assigned tasks or (2) the task allocation is unreasonable or inappropriate. Furthermore, the values of the other two network-level measures (C_{OAK} 0.529 and C_{OTK} 0.671), as indicators of knowledge requirements, are also lower than the average values, showing that the agent has insufficient knowledge and is incapable of completing the required tasks. These factors together contribute to the low level of overall task performance of P01.

With regard to the node-level measures, the mean value of *the congruence of task knowledge needs* (C_{AK}) is 0.650, while each individual agent shows considerable variance in the required knowledge. For instance, the value of the local dealer (A04) is as low as 0.106, while the value of the other three agents (A0301, Buick-nominated suppliers; A0302, Buick-specified brand suppliers; and A0303, Buick-recommended suppliers) reach 1 (see the last column in Table 2). The congruence of task knowledge needs (C_{TK}) gets the average value of 0.684. This means that 38 nodes, or 59% of the tasks, are properly assigned to agents with qualified knowledge, while the remaining 41% of the tasks are improperly assigned.

Optimization Sequence

This study primarily focuses on the optimization of congruence between organizational capabilities and task assignment. The optimization of the knowledge network aims to (1) improve agents' knowledge levels to complete their assigned tasks and (2) adjust task-allocation schemes by replacing or changing the agents who are incapable of executing their tasks. Two key networks are primarily investigated—the organizational knowledge network (AK network) and the organizational assignment network (AT network). The selection of two networks is necessary both for achieving better network-wide performance and for comparing the effect of various optimization sequences. In this study, option A first optimizes the AK network and then the AT network; option B uses the opposite sequence. In contrast to option B, option A can reduce the required number of optimized agents (5 versus 11) and optimized tasks (4 versus 8–10). The total number of required optimizations in option A is also less than the number in option B (7 versus 8–10). This study therefore chooses option A as an efficient optimizing approach for P01. The optimization process is shown in Fig. 2.

It should be noted that the selection of the above sequence ties in with the structure of the AT network. In this case—and particularly with P01—every agent was assigned to multiple tasks. In this situation, the knowledge improvement of an agent will affect a number of tasks and improve the optimization efficiency. But in the opposite situation, where one task was assigned to multiple agents, option B may be more efficient since improving each task network will have an effect on a series of agents.

First Round of Optimization

Round 1 examines an agent's knowledge or the capability required to responsibly complete project tasks. The research uses the following principles to identify agents who have insufficient knowledge for their assigned tasks.

First, the agent should be well connected and influential in a project network. Three indicators are adopted to determine the centrality of an agent in the network: (1) *actual workload based on the knowledge* (AW_K), the contribution of an agents' knowledge to the project's success; (2) centrality authority, which is the agent's pivotal role in the AA network; and (3) the out-degree centrality, which reflects the importance of assignments in the AT network. If an agent has any of the three indicators greater than the first quartile in a similar group, the agent shows considerable influence in the network relations.

Second, the agent should have the capability to accomplish the required tasks. The potential improvement of the agent's performance depends on the measure of *the congruence of agent knowledge needs* (C_{AK}). If an agent's C_{AK} value approaches 1, its marginal improvement is limited to 0. As a result, the study only targets the agents with C_{AK} value less than 1.

Third, the agent's knowledge deficiency should be of a project-specific nature rather than a broad lack of knowledge. In other words, the knowledge deficiency only happens on a specific project but is not a general situation for all prects. This assumption allows the potential for knowledge improvement for a specific project in which a particular agent performs worse than others. To examine the deviation of knowledge deficiency, the coefficient of variation (CV), calculated by $CV = (S/\bar{X}) \times 100\%$, is used to gauge the degree of dispersion in a set of data, where S is the standard deviation and $\bar{X}$ is the mean of the sample. For instance, AW_K measures the knowledge of all agents, so S will be the standard deviation of AW_K for all agents and $\bar{X}$ will be the average value of AW_K for all agents (shown in Table 3). The greater CV implies a higher degree of deviation between an individual agent and the remaining agents. Statistics suggest 5% as a threshold to indicate a minimal difference between an individual and the sample (Tennant 1975). This study endorses this threshold, and the agent will be optimized only if the CV of both AW_K and C_{AK} are higher than 5%.

The process of identifying the potential optimized agents is shown in Table 3. After examining three principles, 5 out of 12 agents were selected as potential agents for the next step, including the PMC director (A02), the local dealer (A04), the structure contractor (A040201), the interior decoration contractor (A040202), and the local detail designer (A0403).

Then, to identify the agents' specific knowledge that needs to be improved, the study further analyzed the AT, AK, and KT networks and conducted face-to-face interviews with project participants. Taking A02 as an example, all relevant networks suggest that A02 needs to complete a total of eight tasks (Fig. 3) and each of these tasks require different knowledge. However, A02 does not possess

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Table 3. Identification of Agents That Need to Be Optimized

Agent number or tier	Criticality			Task completion	Project variation		
	Centrality authority in AA network	Centrality out degree in AT network	AW_K value	C_{AK} value	Coefficient of variation for AW_K	Coefficient of variation for C_{AK}	Identified to be optimized?
A01	0.222	0.188[a]	0.064[a]	0.409[a]	0.008	0	No
A02	**0.414**[a]	**0.125**[a]	**0.093**[a]	**0.565**[a]	**0.269**[a]	**0.276**[a]	**Yes**
A0201	0.461[a]	0.109[a]	0.100[a]	0.875[a]	0.005	0.018	No
A0202	0.552[a]	0.219[a]	0.257[a]	0.949[a]	0.004	0	No
A0301	0.272[a]	0.063	0.029	1.000	0	0	No
A0302	0.222	0.063	0.029	1.000	0	0	No
A0303	0.222	0.078[a]	0.036[a]	1.000	0.082[a]	0.084[a]	No
A04	**0.652**[a]	**0.344**[a]	**0.036**[a]	**0.106**[a]	**0.345**[a]	**0.345**[a]	**Yes**
A0401	0.506[a]	0.094[a]	0.029	0.211[a]	0	0.028	No
A040201	**0.420**[a]	**0.016**	**0.007**	**0.500**[a]	**0.308**[a]	**0.308**[a]	**Yes**
A040202	**0.367**[a]	**0.078**[a]	**0.057**[a]	**0.471**[a]	**0.259**[a]	**0.269**[a]	**Yes**
A0403	**0.314**[a]	**0.047**	**0.036**[a]	**0.714**[a]	**0.159**[a]	**0.163**[a]	**Yes**
First quartile	0.222	0.063	0.029	—	—	—	—

Note: The rows of the selected optimized agents are bold.
[a]Passed the examination of certain respects. Only when all three respects have conformed to the criterion can we identify the agents to be optimized.

all of the required knowledge, such as design knowledge (K0201) or contract-administration knowledge (K0302). Among different types of knowledge, this study selected the most widely connected knowledge types, K0302 and K0305, as optimization objectives, since they have a greater effect on the overall task performance of A02. The former connects with four tasks (T0107, T0203, T0211008, and T0410), and the latter connects with three tasks (T0107, T0203, and T0410) separately. Similarly, the study determined the potential knowledge-improvement fields for the remaining four agents (A04, A040201, A040202, and A0403). As a result, the agents' knowledge can be optimized (the first round optimization) as follows:

- First suggestion: A02 (PMC director) can be trained for improving specific knowledge of K0302 (the contractor administration knowledge) and K0305 (the cost control knowledge), or A02 can be replaced by a new person who has higher K0302 and K0305;
- Second suggestion: A04 (the local dealer) can be trained to improve its K0303 (the procurement management knowledge);
- Third suggestion: The construction knowledge of A040201 (the structure contractor) and A040202 (the interior decoration contractor) will improve their knowledge level of K0503 (the outstanding construction knowledge);
- Fourth suggestion: A0403 (local detailed designer) will be trained for K0203 (the outstanding design knowledge).

Second Round of Optimization

Following the results of round 1, round 2 identifies the improperly assigned tasks. To do that, the value of the *congruence of task knowledge needs* (C_{TK}) has been used because C_{TK} represents the congruence between the task and the required knowledge. If C_{TK} is less than 1, the tasks are not assigned to a proper agent with enough knowledge and can be potentially reassigned. From a total of 64 tasks, 26 had a C_{TK} value less than 1, and among them, 14 tasks improved their C_{TK} value to 1 during the first round of agent optimization. As result, 12 of the 26 tasks still had C_{TK} values less than 1, and they are identified as eligible optimization tasks.

Next, intensive on-site interviews with the field personnel were conducted to determine the feasibility of reassigning those tasks. The interviews showed that several tasks were impossible to reassign because of rigorous 4 S dealership requirements. For example, construction monitoring and acceptance (T0204 and T0306) must be performed by the client, Buick. Contract signing (T0211007) and site preparation (T0403 and T0406) must be organized and performed by the local dealer. After the reality check, four tasks were finally selected to be reassigned. Followed by the four steps of

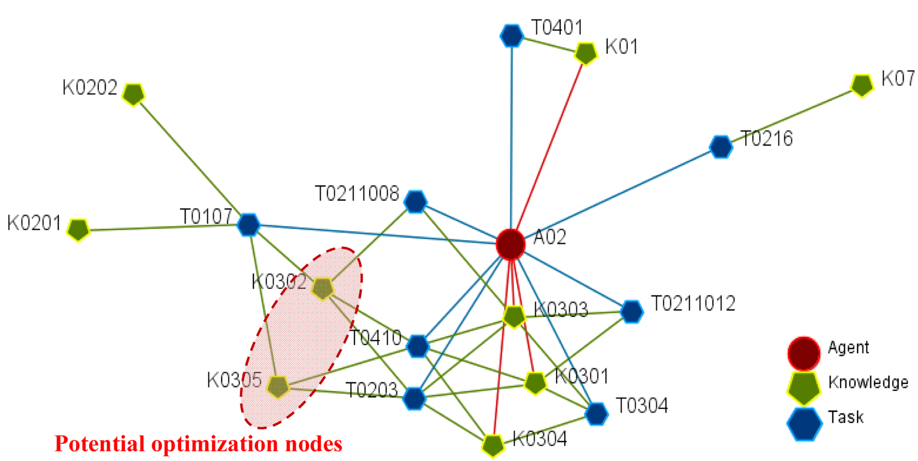

Fig. 3. Metanetwork related to A02

optimization in the first round, the proposed second round optimization includes the following suggestions:

- Fifth suggestion: A0202 (project manager) can assist A01 (Buick representative) to complete T021105 (verify the orders) and T0219 (save the list of main materials and logo furniture), which require procurement management and contract administration knowledge;
- Sixth suggestion: A04 (local dealer) can assist A02 (PMC director) to complete T0216 (confirm the list of main materials and logo furniture) which requires decision-making knowledge in the local context; and
- Seventh suggestion: A02 (PMC director) can assist A0202 (project manager) in completing T0404 (sending the itinerary), which requires project planning knowledge.

Optimization Results and Analysis

After two rounds of optimization, a total of four agents and three tasks were identified for improvement or reassignment. A summary of improved performance is shown in Fig. 4. *Task completion based on the knowledge* (TC_K), which is the best indicator for knowledge-based task completion and overall project performance, increased 47%, from 0.594 to 0.875. Both C_{OTK} and C_{OAK} also improved 24 and 22%, respectively.

Comparing the efficiency of two-round optimization, the first round presents significantly greater improvement than the second round. Each agent reassignment boosted the marginal values of TC_K, C_{OAK}, and C_{OTK} up 7, 4, and 4%, respectively, while each task reassignment only increased the value by 3, 1, and 1%. This evidence demonstrates that the proposed optimization process can increase the congruence between project organization and task completion and that it can also boost the overall project performance. It is suggested that optimizing key agents can generate greater effects on project performance than optimizing tasks because one agent in this case could concurrently complete several tasks. So the improvement of an agent's knowledge can simultaneously influence the completion of several tasks. This is true for most actual projects where tasks are typically divided into small and manageable units, so an agent commonly connects with multiple tasks. As a general implication, an efficient optimization can start from the most-connected nodes (agents) to the least-connected nodes (tasks).

Given the above demonstration of different optimization efficiencies and their effects on project performance, practical optimization strategies should fully recognize the trade-offs among agents, knowledge, tasks, and project performance. Economic principles, such as cost-benefit analysis, should also be endorsed to generate the best achievable and most affordable outcomes. For instance, three main recommendations are proposed in this case: replacing agents, training, and reassigning tasks. For the same benefit that can be achieved by either replacing or training the agent, the latter option should be selected in most circumstances because of its better cost-effectiveness.

Conclusion

Organizational task allocation has become a key issue to determine a project's success because of the diversity of organizational participants, the exploding demand for new knowledge requirements, and the complexity of task composition. To solve the congruence between task assignment and project organizations, this study established a three-dimensional metanetwork model that includes the connections among a project's organization, knowledge, and tasks. Six network measures were discussed to investigate the efficiency of task assignment in a project organization, and the proposed MNA method and measures were validated through a case study of 11 Buick automobile 4 S dealer construction projects in China. The case study identified key agents and tasks that had significant effects on task completion and project performance, and we discussed two rounds of optimization and the results.

This research applies MNA, a valid method for construction organizations, to explain the effectiveness of task assignments in the entire project network, and the main conclusion of this research is summarized as follows: (1) In MNA, both the node-level measures (C_{AK}, C_{TK}, and AW_K) and the network-level measures (C_{OAK}, C_{OTK}, TC_K) present positive correlations with the task assignment and project performance. Among them, TC_K has the highest correlation coefficient with project performance and the best indicators for the congruence of task assignment. (2) The proposed optimal strategies can effectively increase project performance by 47, 24, and 22%, respectively, in terms of measurement of TC_K, C_{OTK}, and C_{OAK}. This indicates that both agents and tasks gain better congruence with appropriate knowledge. (3) Identification of the properly optimized sequences is essential to the task reassignment process because different sequences could lead to various outcomes,

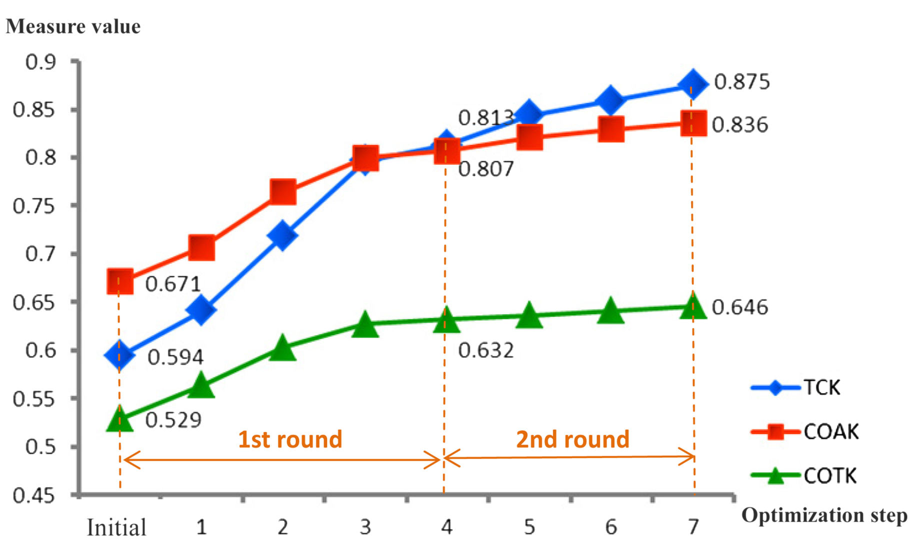

Fig. 4. Performance improvements of two round optimizations

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resources, and efficiencies. Reassignment from the most-connected node to the least-connected node in a network commonly leads to an efficient optimization.

The research explores MNA as a new method for the design, diagnosis, and optimization of project task assignment. MNA can advance the current body of knowledge by accurately modeling the complex interactions between the project tasks and relevant factors. The proposed method can also enhance planning, monitoring, and improvement of task performance in a construction project. When a project starts, this model can be employed to simulate the composition of task assignment and project organization and then to estimate task completion performance. During a project's ongoing processes, the model can help detect improper task congruence by identifying weak agents and ties in the network, and then it can provide corresponding strategies to improve task performance. In reality, the feasibility of optimizing a task is yet dependent on the context and realities of a project, such as its financial or contracting constraints.

There are two main limitations in the research. The dynamic learning process and knowledge improvement of an agent (during the project duration) have not been taken into account; also, project task assignment is a complex process, in which many factors, such as resources, in addition to knowledge and agents, could cause various effects. Future research can incorporate the agent's dynamic learning process into the MNA modeling process and also examine additional influencing factors, such as project resources, organizational culture, or social norms, in order to better simulate the project's actual situation and to design the task assignment.

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Supplemental Data

Tables S1–S4 are available online in the ASCE Library (www.ascelibrary.org).

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