Available online at www.sciencedirect.com

ScienceDirect

International Journal of Project Management 33 (2015) 610 – 622

International Journal of Project Management

www.elsevier.com/locate/ijproman

Measurement model of project complexity for large-scale projects from task and organization perspective

Yunbo Lu [a,b], Lan Luo [a,b,*], Hongli Wang [c], Yun Le [a,b], Qian Shi [a]

[a] School of Economics and Management, Tongji University, Shanghai 200092, China
[b] Research Institute of Complex Engineering & Management, Tongji University, Shanghai 200092, China
[c] School of Business Administration, South China University of Technology, Guangzhou 510640, China

Received 23 December 2013; received in revised form 2 December 2014; accepted 4 December 2014
Available online 29 December 2014

Abstract

Large-scale projects have grown in size, quantity, and complexity; thus, measuring project complexity has become an integral part of project management. This study used the task and organization (TO) perspective to propose a measurement model of project complexity through hidden work that reflected the dynamic "emerging" effect of influencing factors on project complexity. TO measures were identified and mapped with attribute settings of ProjectSim software. The proposed TO measurement method was then expressed as hidden workload divided by direct workload. Overall, 12 hypotheses on the relationship between TO measures and hidden workload were put forth. The Shanghai World Expo construction project was chosen to test the synchronous relationship between hidden workload and project complexity as well as to validate the proposed method. The measurement method could truly reflect the project complexity and therefore can be used to manage the complexity of large-scale projects.

Keywords: Large-scale projects; Project complexity; Measurement model; Hidden workload

1. Introduction

The rapid rate of urbanization in recent years has resulted in an increase in the number of large-scale projects in China with large amounts of dollars invested in infrastructure construction (Hu et al., 2012; World Bank, 2010). Large-scale projects are usually highly complicated (Chan et al., 2004). Lack of relevant knowledge on the part of project managers often results in these projects being beset with issues such as low performance, cost overruns, and schedule delays (Kennedy et al., 2011; Thomas and Mengel, 2008). Therefore, understanding and measuring project complexity are significant for large-scale projects because it can serve as a reference for decision makers and managers involved in the projects (He et al., 2014).

Project complexity is defined as the inherent characteristics of a project that result from its various interconnected parts (Xia and Chan, 2012). Project complexity involves dynamism and uncertainty (Baccarini, 1996; Geraldi and Adlbrecht, 2007), which are mainly manifested in task and organizational complexities (Baccarini, 1996; Li et al., 2009). Various authors have attempted to measure project complexity through case studies and surveys. However, previous studies on project complexity are limited, as most studies have focused only on the conceptual framework of project complexity (Maylor et al., 2008; Sinha et al., 2006). Existing methods of measuring project complexity are based mainly on the macro-perspective, and ignore emergency features rooted in micro-influencing factors. To address this drawback, the present study aims to develop a complexity measurement model for large-scale projects that considers emerging characteristics of project complexity, which are also distinct from others.

Computational organization science, a growing interdisciplinary area centered on the development of organization theory through the use of computational techniques (Carley, 1994), is a neo-information processing approach to the study of social, organizational, and policy systems that combines social

* Corresponding author at: Room 911, Tongji Building Block A, No.1 Zhangwu Road, Shanghai, P.R.China, 200092.
E-mail address: mengling2391@163.com (L. Luo).

http://dx.doi.org/10.1016/j.ijproman.2014.12.005
0263-7863/

science, computer science, and network analysis (Carley, 2002a, 2002b). Computational organization modeling is called the thought experiment, and relative to the induction, deductive, computational organization modeling expresses people's ideas in a more intuitive way (Prietula et al., 1998). The hypothesis may be simple, but the conclusion may not be obvious. Relative to the theory of mathematics, physics and engineering, the lack of comparable referents makes it difficult for researchers to assess the effectiveness of modeling (Axtell, 2001). Computational organization theory is based on simulation and organization science, but for the model validation, it is difficult to directly copy the validation method of the natural engineering system, and also transcend the traditional empirical methods, on which scholars have reached consensus (Axtell, 2001; Carley, 2002a, 2002b; Sargent, 1992). Virtual Design Team (VDT), based on the extended information-processing view of organizations, attempts to develop 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 (Yan and Levitt, 1996).

Numerous "hidden works" exist in large-scale projects; these hidden works are caused by influencing factors of project complexity and are ultimately reflected on rework, coordination, and waiting work. Hidden work provides a direct reflection of the extent of project complexity. Therefore, project complexity can be measured indirectly by hidden workload. VDT can reflect the dynamic emergence of micro-elements and predict accurately the actual project schedule, quality, cost, hidden work, and all types of risks caused by work backlog, thereby compensating for the shortage of predicting hidden workload quantitatively. Thus, with the help of ProjectSim and from the task and organization (TO) perspective, a measurement model of project complexity is proposed in this study. The model uses hidden workload that reflects the dynamic "emerging" effect of influencing factors on project complexity.

The paper is organized as follows. Section 2 reviews recent studies on project complexity and measurement in construction projects. Section 3 analyzes the factors of task and organizational complexities. Section 4 develops a measuring model from hidden workload, followed by a case study of the 2010 Shanghai Expo construction project in China to demonstrate the relationship between hidden workload and project complexity in Section 5. The final section presents the conclusions for the proposed model.

2. Literature review on project complexity and measurement

2.1. Project complexity definition

Complexity is a term that is difficult to define and even more difficult to quantify precisely. Thus, most scholars define complexity from the perspectives of their own fields, and a consensus on its definition has not been reached (Corning, 1998). The dictionary simply defines complexity as the characteristic of having a large number of interacting parts; essentially, the science of complexity is the study of these interactions.

Complexity has been recognized as one of the most relevant topics in project management research (Cicmil et al., 2006). Interest in the complex dimension of projects is new and significant efforts began to be reported only in the late 1990s (Baccarini, 1996). During this period, the explicit study of complexity in projects began. Baccarini (1996) defined project complexity as "consisting of many varied interrelated parts" and can be operationalized in terms of differentiation and interdependency. In the definition, differentiation refers to the number of varied components of the project (tasks, specialists, subsystems, and parts), and interdependency refers to the degree of interlinkages among these components. Williams (1999) highlighted project complexity as structural complexity, the number and interdependence of elements (following a paper by Baccarini (1996)), and uncertainty in goals and means (following a paper by Turner and Cochrane (1993)). In addition, Vidal et al. (2010) classified complexity into four categories: project scale, differentiation of project elements, interaction of project elements, and interaction with external environment; and further stressed that these factors constitute the necessary and insufficient conditions for project complexity. Geraldi et al. (2011) summarized that project complexity includes structural, uncertainty, dynamics, pace, and sociopolitical complexity.

Most authors emphasized the influence of interdependencies and interactions of various elements on project complexity (Ivory and Alderman, 2005). Other authors regarded project complexity as having non-linear, highly dynamic, and emerging features. Vidal et al. (2011), for example, proposed the definition of project complexity as "the property of a project which makes it difficult to understand, foresee, and keep under control its overall behavior, even when given reasonably complete information about the project system."

In conclusion, studies on the concept of project complexity have been conducted for years; the lack of consensus on the definition of project complexity has resulted in difficulty in understanding this concept. Thus, the present study proposes that project complexity can be defined as "consisting of many varied interrelated parts, and has dynamic and emerging features" (Baccarini, 1996; Geraldi and Adlbrecht, 2007).

2.2. Measurement methods of project complexity

Project complexity is an emerging but critical topic in construction project management. Researchers have increasingly recognized the importance of complexity, particularly in large-scale projects (Baccarini, 1996; Chryssolouris et al., 1994; Frizelle and Woodcock, 1995; Little, 1997; Wiendahl and Scholtissek, 1994). Thus, several attempts have been made to measure the project complexity (Table 1).

Given the fact that project complexity is difficult to quantify precisely, a number of studies have focused on identifying factors or aspects relating to project complexity (Xia and Chan, 2012) and attempted to measure complexity factors to build a framework that describes project complexity qualitatively, such as project complexity model (Vidal and Marle, 2008), five-dimensional model (Owens et al., 2012), framework in large engineering projects (Bosch-Rekveldt et al., 2011), and

Table 1
Previous research about measuring project complexity in construction projects.

Author (year)	Results
Gidado (1996)	Proposed an approach that measures the complexity of the production process in construction
Sinha et al. (2006)	Described a framework for measuring the complexity of a project, and put forward complexity index (CI)
Maylor et al. (2008)	Reported a grounded model for managerial complexity
Vidal and Marle (2008)	Developed the project complexity model (attributes, links, objects, events, ALOE)
Remington et al. (2009)	Revealed a wide range of project complexity factors
Geraldi et al. (2011)	Summarized the project complexity framework through systematic literature review
Wood and Ashton (2010)	Developed a model to measure the complexity at an early stage in a project using mixed methods
Vidal et al. (2010, 2011)	Used analytic hierarchy process (AHP) and formulated a project complexity measure model to assist in the decision making of project managers
Bosch-Rekveldt et al. (2011)	Built Technical, Organizational and Environmental (TOE) framework to grasp project complexity in large engineering projects
Lebcir and Choudrie (2011)	Developed the project complexity framework in construction projects
Giezen (2012)	Analyzed the advantages and disadvantages of reducing complexity in mega-project planning
Gransberg et al. (2012)	Developed the "complexity footprint" for complex projects
Owens et al. (2012)	Developed a five-dimensional model adding context and finance
Shafiei-Monfared and Jenab (2012)	Measured the relative complexity of design projects using managerial and technical graphs and complexity design structure matrix (CDSM)
Xia and Chan (2012)	Measured the degree of building project complexity, and developed a complexity index (CI) using the Delphi method
Lessard et al. (2013)	Built house of project complexity to understand complexity in large infrastructure projects

framework of project complexity in large infrastructure projects (Lessard et al., 2013). Wood and Ashton (2010) developed a model composed of two stages in relation to the five themes of project complexity to measure complexity at an early stage in a project. Lebcir and Choudrie (2011) also developed a project complexity framework for construction projects, whereas Geraldi et al. (2011) summarized the project complexity framework through a systematic literature review. Research on measuring project complexity is limited, with most studies focusing only on the conceptual framework of project complexity.

Several authors have attempted to measure project complexity quantitatively. For instance, Sinha et al. (2006) proposed a framework for measuring project complexity and described a measure in the form of an index. Xia and Chan (2012) identified several key parameters to measure building project complexity using the Delphi survey, calculated the individual importance weightings, and obtained the complexity index (CI). Vidal et al. (2010, 2011) used the analytic hierarchy process and formulated a project complexity measure model based on system thinking to assist in the decision making of project managers. Shafiei-Monfared and Jenab (2012) measured the relative complexity of design projects using managerial and technical graphs and a complexity design structure matrix. Maylor et al. (2008) reported a grounded model and investigated the perceptions of project managers. Remington et al. (2009) revealed a wide range of project complexity factors by interviewing 25 project managers. Gransberg et al. (2012) developed the "complexity footprint" based on the detailed study conducted by an international research team on 18 complex projects.

Generally, these previous studies built project complexity frameworks from different perspectives, and utilized case studies and surveys as research methods. These methods usually include the following steps. First, an indicator system is built through a literature review. Second, an expert survey is used to grade the weights of various indicators. Finally, the value of complexity is calculated by multiplying the indicator vector by weight. In these studies, the most important factor is the assumption that project complexity is linear and can be added by weight directly. In fact, project complexity is a nonlinear and emerging behavior. Thus, the present study aims to address this drawback by developing a complexity measurement model for large-scale projects, which considers the emerging characteristics of project complexity that are distinct from others.

3. TO measures

3.1. TO concept model

Many scholars have conducted studies to identify and categorize the measurement factors. For instance, Baccarini (1996) classified project complexity into organization complexity and technology complexity; organization complexity includes the amount of vertical organizational hierarchy, amount of component unit of organization, and so on, whereas technology complexity includes task, material, and knowledge characteristics. Taikonda and Rosenthal (2000) connected innovation of the technique with the maturity of an organization; in their opinion, immaturity of an organization leads to task uncertainty. Maylor et al. (2008) identified the elements of project complexity as mission, organization, delivery, stakeholders, and team. Maylor (2003) classified project complexity into three categories: organization, resource, and technique complexity. Remington and Pollack (2007) divided the influencing factors of project complexity into four dimensions: members' experience and ability to cope with project complexity within different types and degrees, organizational structure and coordination between project and other key participation aspects, culture of project, and business process of project. Brockmann and Girmscheid (2007) divided complexity into five categories: task, society, culture, operation, and cognition complexity.

Several scholars have also summarized the categories of project complexity as reported in Table 2. Table 2 shows that every scholar has different categories of project complexity, but based on this list, one can conclude that task complexity and

Table 2
Types of project complexity.

Author (year)	Types of project complexity
Baccarini (1996)	Organizational complexity and technological complexity
Maylor (2003)	Organizational complexity (including the number of members, departments, organizations, regions, nations, languages, time zones, level of the organization, and power structure), resource complexity (project scale and size of the budget), and technological complexity (technology, innovation system, uncertainty of the process or demand)
Geraldi and Adlbrecht (2007)	Complexity of fact, complexity of faith, and complexity of interaction
Girmscheid and Brockmann (2008)	Task complexity, social complexity, cultural complexity, operative complexity, and cognitive complexity
Remington and Pollack (2007)	Structural complexity, technical complexity, directional complexity and temporal complexity
Bosch-Rekveldt et al. (2011)	Technological complexity (goals, scope, tasks, experience, and risk), organizational complexity (size, resources, project team, trust, and risk) and environmental complexity (stakeholders, location, market conditions and risk)
Senescu et al. (2012)	Product complexity, organization complexity, and process complexity

organization complexity are key aspects of project complexity. Using these reviews, the present study proposes a TO framework of project complexity to measure the complexity of large-scale projects. The TO concept model proposed in the present study divides influencing factors of project complexity into two parts and includes not only the objectivity task and subjectivity organization, but also the interactive relationship among tasks and organizational members as shown in Fig. 1.

3.2. Task complexity factors

Large-scale projects involve numerous participants and have mutual influence and restriction in time and space among task activities (Li et al., 2009). These projects also involve numerous tasks from multiple fields, including not only engineering and technology, finance, and organization management, but also ecological protection, social stability, and energy saving. These tasks are not isolated, and have a variety of direct or hidden connections. Each task is affected by a change in other tasks and leads to a corresponding change in other tasks. Each task has complex nonlinear interaction with others, which causes an increase in project complexity.

3.2.1. Amount and complexity of task

(1) Amount of task
The influence of amount of task on project complexity is mainly manifested in the differences among numerous tasks. Thus, project managers have to adopt different

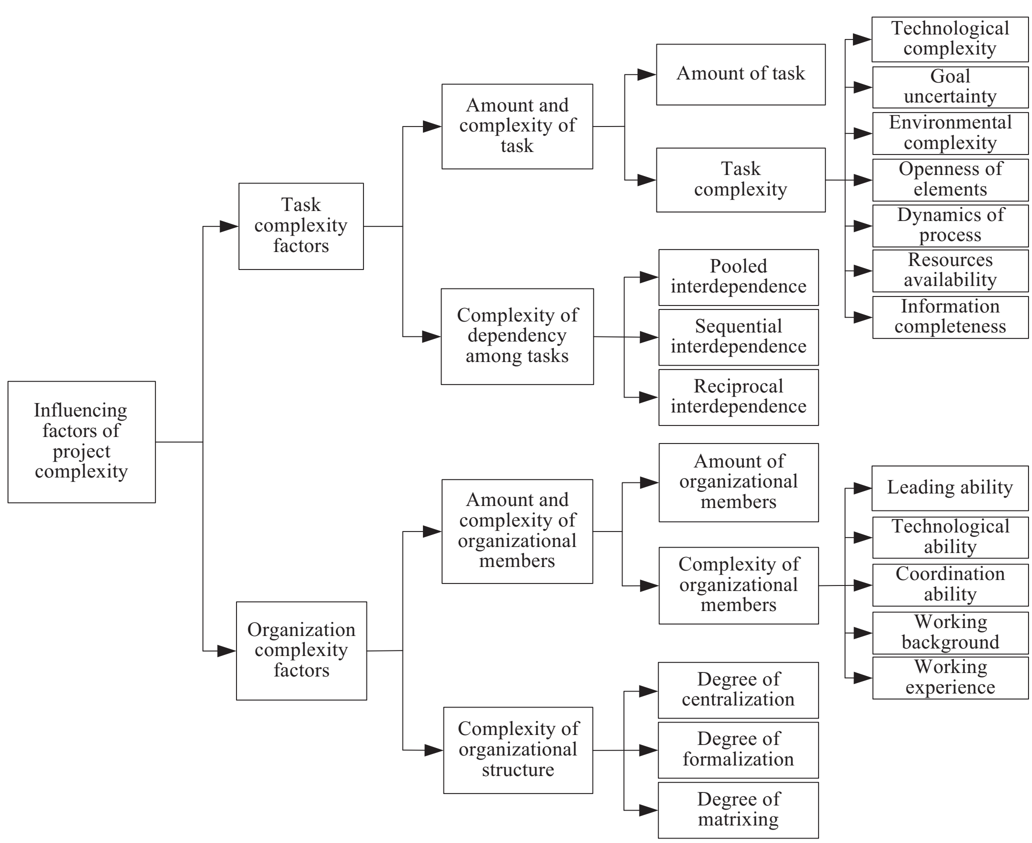

Fig. 1. Influencing factors of project complexity from TO measure model.

strategies to address these differences, resulting in an increase in the complexity of project management.

(2) Task complexity

1) Technological complexity: It refers to the knowledge and skill that a technology requires. Large-scale projects are typically characterized by high technological complexity, such as overlapping of design and construction works, building type, and dependency on project operation (He et al., 2014). The increasingly popular trend of including innovative and green technologies in construction, such as three-dimensional technology, energy conservation technologies, and new construction materials also contribute to the technical complexities in managing mega-construction projects (Harty et al., 2007; Hu et al., 2014). Thus, technological complexity is one of the important factors that affect project complexity.

2) Goal uncertainty: It is usually caused by several factors, such as the requirements of various project participants, project task complexity, and limited resources (He et al., 2014). Williams (1999) stated that goal complexity is a type of structural complexity because almost all projects have multiple objectives. Large-scale projects not only achieve managerial goals such as quality, cost, and schedules, but also achieve functional goals such as technology, economy, and security (Li et al., 2009). These different levels of goals increase the project complexity.

3) Environmental complexity: It refers to the complexity of a context where a project operates, such as the natural, market, political, and regulatory environments (Li et al., 2009). Bosch-Rekveldt et al. (2011) added that this complexity could also be influenced by the complexity of project stakeholders whose interests and needs are affected by the environment. This statement is echoed by Brockmann and Girmscheid (2007), who proposed social complexity to define the complexity caused by the number and diversity of project stakeholders. All environmental factors increase project complexity.

4) Openness of elements: A project is affected by various external factors, and a project and its tasks have material, energy, and information exchange with the external environment. A project is influenced by external factors in the process of implementation, which leads to unpredictable results, making the openness of elements one of the important causes of project complexity.

5) Dynamics of process: When the project is affected by the external environment, its elements also change constantly, even changing beyond the initial expectations and becoming difficult to control. The dynamics increase the uncontrollability of project implementation, causing the project to become more complex. Thus, dynamic elements in the process of implementation constitute another important factor that affects project complexity.

6) Resource availability: In the process of project implementation, project tasks have a different time and place; therefore, resource utilization also differs. This condition results in the need for mutual coordination of tasks, which increases project complexity.

7) Information completeness: From the perspective of information theory, the task of implementation is essentially a process of information collection, process, and application. Information complexity stems from complicated communication among a large number of project stakeholders under complicated contractual arrangements throughout the entire project delivery process (He et al., 2014). Information completeness rather than information complexity was used to reflect the complexity of specific tasks. If information completeness is low, then the complexity of task completion is high.

3.2.2. Complexity of dependency among tasks

The dependency among tasks can be divided into the following types of interdependence: pooled, sequential, and reciprocal (Thompson, 1967).

(1) Pooled interdependence

Each part of the task elements has a discrete contribution to the whole and each is supported by the whole (Thompson, 1967). In this situation, each task is performed by a different group of people, and the only connection among tasks is summarized outputs as a whole.

(2) Sequential interdependence

X must act properly before Y can act (Thompson, 1967). Before a subsequent task can begin, the preceding task has to be completed. That is, the output of the former serves as the input for the latter.

(3) Reciprocal interdependence

The output of each task becomes the input for the other, which signifies contingency (Thompson, 1967). When the output of a task is the input of a subsequent task, the output of another task is also the input of the former task. The information flow among tasks circulates back and forth within a certain period (e.g., reciprocal interdependence occurs between project preliminary design and design coordination).

Among these three relationships, reciprocal interdependence causes an increase in project complexity because of the interactions among information, which result in major rework and coordination, thereby increasing project complexity.

3.3. Organization complexity factors

The execution of a project is conducted by a project organization that involves project staff, organizational structure, and various teams. Consequently, project complexity is also manifested by organizational complexity. As the most central part of project complexity, organizational complexity, such as members' experience, number of hierarchies, and departments of organizational structure, has received increasing attention in the past two decades (Baccarini, 1996; Bosch-Rekveldt et al., 2011; Xia and Lee, 2004).

3.3.1. Amount and complexity of organizational members

(1) Number of organizational members
The number of organizational members plays a limited role in project complexity. However, difficulties in communicating and coordinating during the process caused by member differences are an important reason for project complexity; simultaneously, the increasing number of members also leads to increased levels of organization and management amplitudes. Therefore, the number of organizational members is one of the important factors that affect project complexity.

(2) Complexity of organizational members
1) Leadership skill: This skill affects project complexity by making a difference in the coordination workload of the entire project. That is, the stronger the leadership skill is, the more smoothly members communicate with one another, and dependency among tasks has minimal influence on project complexity.
2) Technological skill: This skill can help reduce technical dependency among organizational members if members possess the required technological skill that will enable them to complete their work by themselves. Having technological skills can aid in reducing rework and coordination workload. Therefore, technological ability is related to project complexity. The stronger the technological skill, the lesser the project complexity.
3) Coordination skill: To fulfill the goal, members are expected to communicate with one another when they encounter difficulty with their own work; thus, coordination skill affects rework, coordination, and waiting workload.
4) Working background: This factor reflects the education degree of members and their competency in previous jobs. Thus, working background is one of the most important factors that affect project complexity.
5) Working experience: This factor reflects the members' coordination and cooperation skills; thus, it is one of the most significant factors that affect project complexity.

3.3.2. Complexity of organizational structure

(1) Degree of centralization
Centralization is used to describe the degree of concentration of rights and decisions in an organization. Generally, if the project tasks are sequentially interdependent and have limited project complexity, the degree of centralization is relatively high; thus, the upper echelons of the organization usually make decisions. Conversely, if project tasks are executed concurrently, which indicates the presence of a higher project complexity, the degree of centralization is relatively low; thus, project managers would give rights to the entire team to make decisions independently.

(2) Degree of formalization
Formalization is used to describe the degree of utilization of rules and procedures of organizational behaviors. Generally, if project tasks are sequentially interdependent, which means limited project complexity, the formalization is relatively high; thus, these tasks are executed under strict rules and procedures. Conversely, if project tasks are executed concurrently, which means higher project complexity, formalization is relatively low. In this situation, team members would have more freedom to make decisions independently.

(3) Degree of matrixing
Matrixing is used to describe the degree of connectedness between organizations. In a project organization with a high matrix structure, members tend to exchange informal information and adopt informal meetings. Conversely, in a project organization with a low matrix structure, members often adopt official methods of information exchange.

4. Measurement model of project complexity

4.1. VDT introduction

According to Thompson (1967), an organization includes three types of coordination mechanism. The first is standardization, which refers to a common coordination of organization and process; the second is mutual adjustment, which refers to additional rework and coordination work caused by exception; and the third is planning, which is characterized by a dynamic and predicted structure. The VDT model expresses only the first and second types of coordination. Levitt (2012a, 2012b) stated that the existing VDT model cannot achieve planning of dynamic characteristics. This limitation results in a major error when the VDT model is used to predict the hidden workload and duration of complex projects. The error stems mainly from the following causes: (1) VDT does not reflect the spontaneity and initiative characteristics of an agent, and cannot change a plan automatically when the plan does not match reality; and (2) VDT does not simulate intervention and optimization automatically in the process of project management, and cannot provide the automatic project performance output of dynamic adjustment and optimization planning.

Therefore, the computational project organization and process (CPOP) model was used; this model is the core principle of ProjectSim software proposed by Dr. Lu Yunbo from Tongji University and is a research achievement supported by several projects of the National Natural Science Foundation of China and related subjects (Lu et al., 2010, 2013). The principle of CPOP is similar to that of VDT, which was proposed by Cohen and Levitt (1991). However, CPOP has improvements based on VDT. As an extension of VDT, CPOP increases "planning coordination" to ensure better prediction of the hidden workload and duration of a complex project. The core principle of ProjectSim includes the following (Lu et al., 2013): (1) Extending information-processing and coordination theory. CPOP is the basic model of such theory; (2) simulating project tasks and process. CPOP defines four critical attributes, namely, workload, complexity, uncertainty, and skill requirement, as well as recognizes four types of interdependency relationship in direct work, including coupled, sequential, reciprocal, and objective interdependence. CPOP simulates direct and hidden works, and regards an organization as an "exception processing machine" to simulate the emergence of work exception and hidden work; (3) simulating micro-behavior and micro-activity of organizational members. CPOP further comprehends the qualities and bounded rationality theory, identifies the critical attributes of the agent, and designs specific microscopic behavior and activities of the agent; (4) simulating organizational cooperation. CPOP identifies organizational structure as vertical controlling structure and horizontal communication structure, and identifies four organizational attributes, including team experience, centralization, formalization, and matrixing; (5) considering comprehensive macro-performance. CPOP outputs five types of quantitative prediction, including hidden work, duration, human resource cost, quality, and work backlog.

The entire framework of CPOP is illustrated in Fig. 2. In CPOP, direct work is the initial input, while the project organization and agent form the executive system. Emerging hidden work refers not only to the dynamic output but also to the dynamic input. Simulation output is used to express the project results. The micro-contingency view was used to create a CPOP model to predict hidden workload accurately and provide a quantitative design for project organization and process. The computer program can visually create a project management model, simulate the emergence of hidden work, predict potential risks accurately, and develop management strategies (Lu et al., 2010).

The ProjectSim simulation software, which is based on the theory of CPOP, creates work process and organizational structure conceptualization and graphics with clear charts. This visual modeling can clarify the relevance of the organization and project as well as contribute to the effectivity of organizational design and personnel management. At the same time, the modeling simulates a large amount of data and all kinds of charts with an intelligent agent of the simulation engine and behavior matrix, thereby aiding users in identifying potential bottlenecks and ensuring effective project management.

4.2. Mapping TO measures with ProjectSim

The mapping of TO measures of project complexity with ProjectSim is presented in Fig. 3.

4.2.1. Mapping T measures with ProjectSim

(1) Mapping amount and complexity of task
Amount of task: ProjectSim does not set the "amount of task" but sets specific properties of each task; thus, the amount of tasks can be determined indirectly through the superposition of each task. The amount of tasks itself has a minimal effect on project complexity; rather, the difference among tasks increases project complexity.
Complexity of task: This metric includes seven factors, namely, technological complexity, goal uncertainty, environmental complexity, openness of elements, dynamics of process, resource availability, and information completeness. The weighted average is used to map these factors with the attribute settings of ProjectSim. Technological complexity corresponds to the solution complexity in ProjectSim, whereas resource availability and information completeness correspond to requirement complexity in ProjectSim, as well as goal uncertainty, environmental complexity, dynamics of process, and openness of elements correspond to task uncertainty in ProjectSim.

(2) Mapping complexity of dependency among tasks
Dependency among tasks can be divided into pooled, sequential, and reciprocal interdependence. Pooled interdependence is caused by multiple tasks in parallel without any relationship between tasks in the process, which is difficult to quantify in ProjectSim. Therefore, in this study, only the two other interdependencies with attribute settings in ProjectSim were mapped. Sequential interdependence corresponds to sequential interdependence in ProjectSim, whereas reciprocal interdependence corresponds to rework, communication, and parallel relationship.

4.2.2. Mapping O measures and ProjectSim

(1) Mapping amount and complexity of organizational members
Amount of organizational members: This factor is similar to the amount of task, which is not considered, and can be expressed by the number of members in each position.
Complexity of organizational members: This factor includes leadership, technological, and coordination skills,

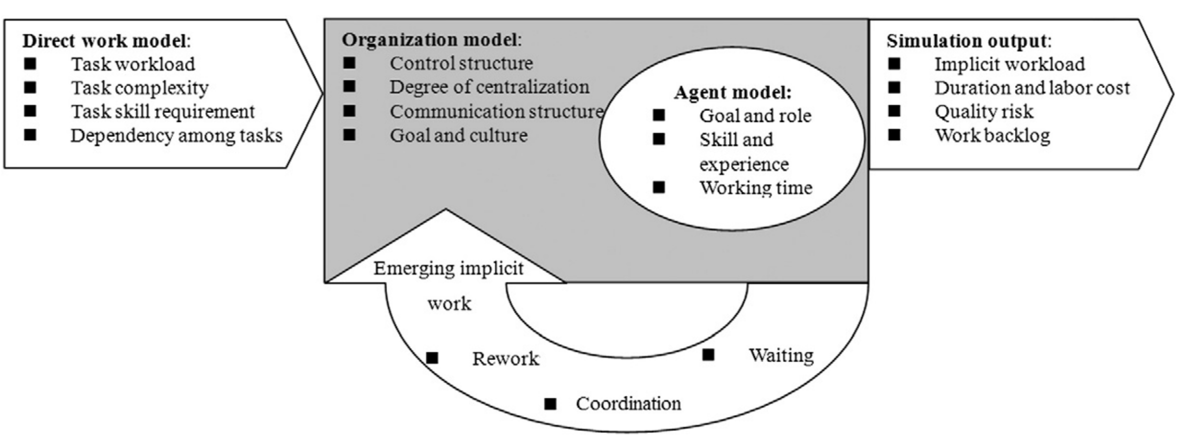

Fig. 2. Framework of CPOP.

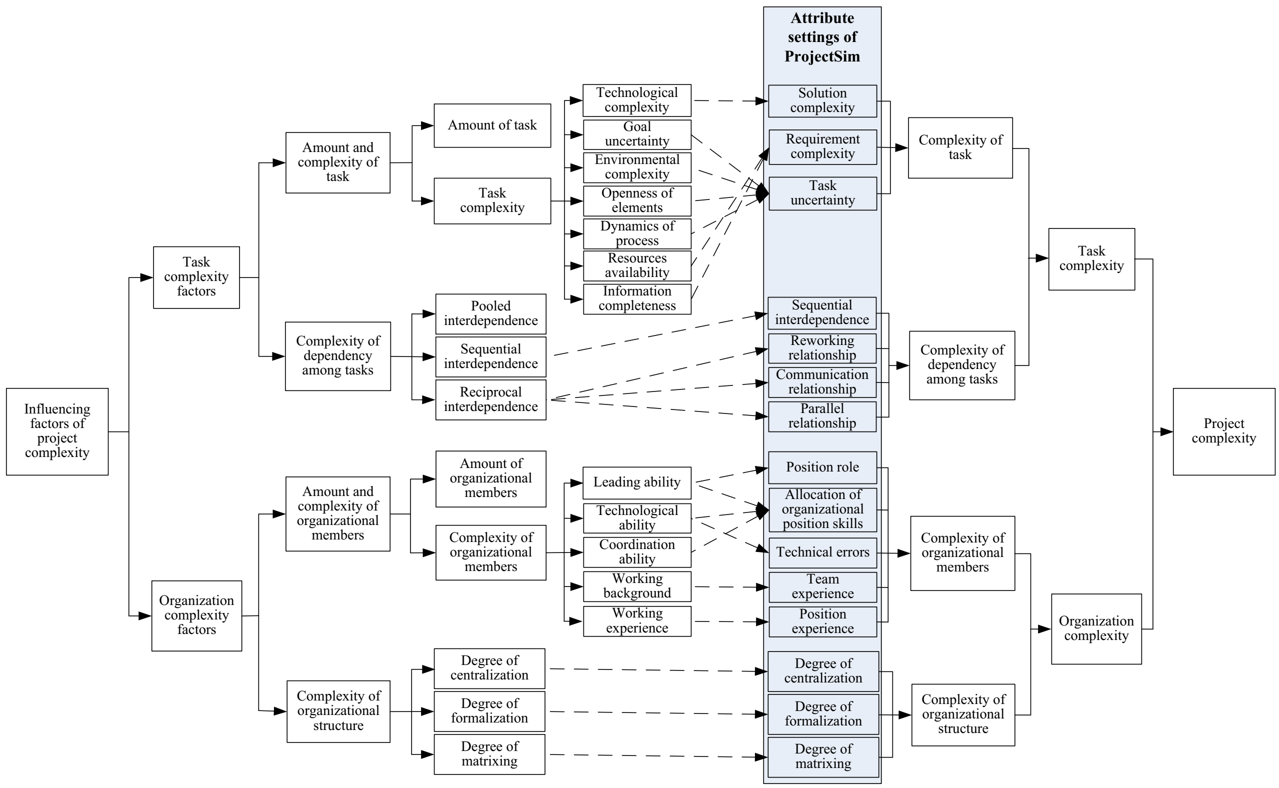

Fig. 3. Mapping TO measures of project complexity with ProjectSim.

as well as working experience and working background. Leadership skill can be expressed by role orientation and allocation of organizational position skill in ProjectSim. Technological skill can be expressed by the allocation of organizational position skill and technical errors of organization members in ProjectSim. Coordination skill corresponds to the allocation of organizational position skill in ProjectSim. Working background corresponds to team experience in ProjectSim, whereas working experience corresponds to position experience in ProjectSim.

(2) Mapping complexity of organizational structure
Organizational structure can be divided into centralization, formalization, and matrixing. These items have one-to-one correspondence.

4.3. TO measure method based on hidden workload

Hidden work is a relative concept of direct work, which denotes the dynamic emergency activity of rework, coordination, and waiting during the process of completing the direct work. Hidden work has characteristics of concealment, derivativeness, and randomness. When project workers cannot complete certain tasks because of personal factors (e.g., behavior, skill, and experience), organizational constraints (e.g., organizational structure, knowledge distribution, and coordination strategy), or task uncertainty (e.g., lack of information) that leads to the "exception" or emerging demand and coordination, and when coordination of demand cannot obtain a timely response, waiting or "exception" spreads in the organization and task networks at the same time until they are effectively solved by certain workers or ignored. That is, rework is needed to solve the "exception" effectively, and more "exception" may emerge if the "exception" is ignored.

Every large-scale project has numerous "hidden works" caused by influencing factors of project complexity that are ultimately reflected in rework, coordination, and waiting work. Hidden work is a result of project complexity and its workload directly reflects the extent of project complexity. Therefore, project complexity can be measured indirectly by hidden workload. ProjectSim measures hidden workload with the emerging dynamic interaction of rework, coordination, and waiting workload, and compares hidden workload with direct workload to provide an objective reflection of project complexity as Eqs. (1) and (2).

$$Project\ complexity = Hidden\ workload / direct\ workload \tag{1}$$

$$Hidden\ workload = ProjectSim\ (T, O) = rework\ workload + coordination\ workload + waiting\ workload \tag{2}$$

Note: The calculation unit of all workload is "day/person".

The preceding analysis indicates the presence of the relationships between TO measures and project complexity. The synchronal relationship between hidden workload and project complexity is proved by proposing 12 hypotheses in which hidden workload is related in terms of the TO measure method by combining the micro-influencing factors. If all the hypotheses are supported, then one can conclude that the higher the amount of hidden workload, the higher the project complexity, and vice versa. The TO measure method could also be proven effective.

Hypothesis 1. The higher the solution complexity, the higher the amount of hidden workload.

Hypothesis 2. The higher the requirement complexity, the higher the amount of hidden workload.

Hypothesis 3. The higher the task uncertainty, the more the hidden workload.

Hypothesis 4. The stronger the rework relationship among tasks, the higher the amount of hidden workload.

Hypothesis 5. The stronger the communication relationship among tasks, the higher the amount of hidden workload.

Hypothesis 6. The stronger the parallel relationship among tasks, the higher the hidden workload.

Hypothesis 7. The higher the amount of technical errors of organization members, the higher the amount of hidden workload.

Hypothesis 8. The more team experience, the lesser the amount of hidden workload.

Hypothesis 9. The more position experience, the lesser the amount of hidden workload.

Hypothesis 10. The higher the degree of centralization, the higher the amount of hidden workload.

Hypothesis 11. The higher the degree of formalization, the lesser the amount of hidden workload.

Hypothesis 12. The higher degree of matrixing, the lesser the amount of hidden workload.

5. Case study

The AB area of the 2010 Shanghai World Expo construction project was used as a construction simulation model to verify the hypotheses and prove the relationship between hidden workload and project complexity.

5.1. Introduction to World Expo project

The 2010 Shanghai World Expo construction project, with a total investment of RMB 28 billion and a floor area of 2.4 million m^2, is a large-scale project (Expo Shanghai China, 2010). The construction period spanned 37 months and consisted of over 400 single projects. The Shanghai Expo construction headquarters comprised 10 functional management divisions and 10 on-site project management teams (SECH, 2008, 2009). Thus, the Shanghai Expo project is a typical example of a large-scale project in China. The AB area of the World Expo project was chosen for the case study for the following reasons:

(1) The AB area has not only general tasks but also complex tasks with significant uncertainty and high technical requirements, which would enable the effective analysis of the effects of different tasks on project complexity. In addition, the complex relationship among various tasks results in substantial rework, coordination, and waiting work, which fits the measuring project complexity through the hidden workload.
(2) The organizational structure of the AB area is a mainstream model of joint management by owners and professional consulting company and has typical significance in large-scale projects. The structure and members have certain representativeness; thus, analyzing the effect of the organization on project complexity can provide guidance for project managers.
(3) Our research team was responsible for the consulting service; thus, the researchers are highly familiar with this project. Collecting data from the project was convenient for the researchers.

5.2. Constructing the model on ProjectSim

The ProjectSim model was constructed through the following steps. First, parameters were collected based on the actual project. These parameters were then mapped with the ProjectSim model. Second, the task flowchart and organization structure chart were expressed and connected to form the conceptual model. Finally, the project model was revised based on the results of the simulation.

The practical parameters were set as follows: (1) 79 tasks were identified in the AB area of the World Expo project, and seven influencing factors of task complexity were mapped with ProjectSim. (2) Through fieldwork and interviews, 24 tasks were identified to correspond to rework relationship, 141 tasks to communication relationship, and 15 tasks to parallel relationship. (3) Considering the project reality, the researchers set the degree of centralization, degree of formalization, and strength of matrixing to medium, and mapped them with ProjectSim. (4) The five influencing factors related to complexity of organization members were mapped with ProjectSim. The working time of members was regulated as eight hours a day, six days a week; one project manager and one deputy project manager were appointed in the project model. Four team members were dispatched to the technology department, six to the engineering department, three to the coordinating department, and two to the comprehensive department.

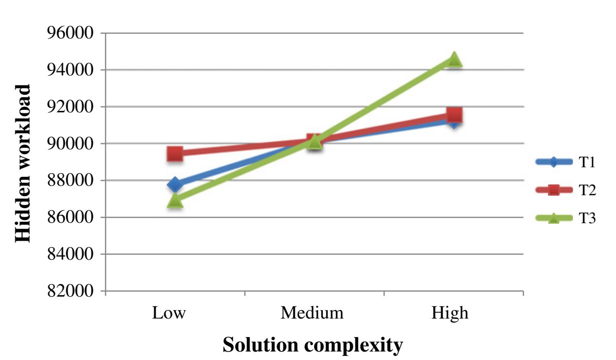

Fig. 4. Relationship between solution complexity and hidden workload.

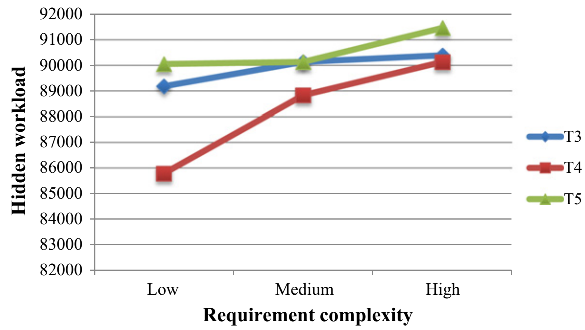

Fig. 5. Relationship between requirement complexity and hidden workload.

5.3. Hypothesis testing

5.3.1. Hypothesis testing of task complexity

Three tasks were selected to verify the hypothesis. The simulation results of the relationship between solution complexity, requirement complexity, task uncertainty, and hidden workload are shown in Figs. 4–6, respectively.

Fig. 4 shows that the increase in solution complexity and hidden workload of the entire project also increased, which supports Hypothesis 1. Fig. 5 indicates that the hidden workload of the entire project also increased with the increase in requirement complexity, which supports Hypothesis 2. Meanwhile, Fig. 6 shows that an increase in complexity of task uncertainty resulted in an increase in the hidden workload of the entire project, which supports Hypothesis 3.

5.3.2. Hypothesis testing of dependency relationship among tasks

Three groups of tasks that have rework relationship were chosen to simulate and verify the hypothesis. The simulation results are shown in Figs. 7. The figure indicate that an increase in the strength of the rework relationship resulted in an increase in the hidden workload of the entire project, which supports Hypothesis 4.

The simulation result of the relationship between communication relationship and hidden workload is shown in Fig. 8. The figure shows that with the increase in the strength of communication relationship, an increase in the hidden workload of the entire project can also be observed, which supports Hypothesis 5.

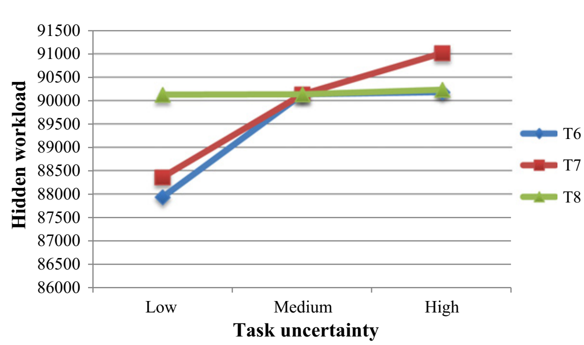

Fig. 6. Relationship between task uncertainty and hidden workload.

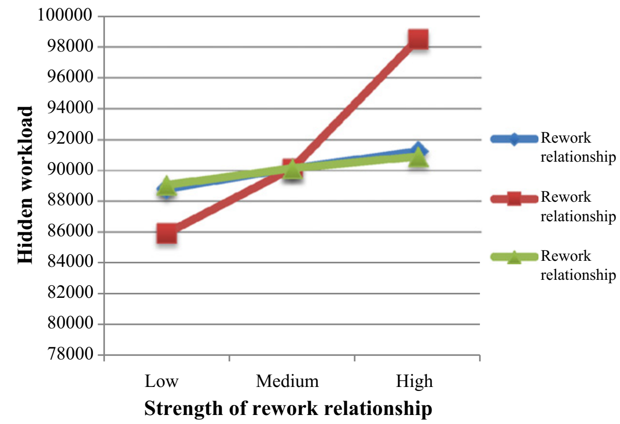

Fig. 7. Relationship between rework relationship and hidden workload.

Two groups of parallel relationship on the critical path and two groups of parallel relationship on the non-critical path were chosen to verify the hypothesis. The simulation results are shown in Figs. 9. The figures illustrate that the hidden workload of the entire project increased with the increase in strength of the parallel relationship, thereby supporting Hypothesis 6.

5.3.3. Hypothesis testing of organizational members

The simulation results of the relationship between technical errors, team experience, and position experience of organizational members and hidden workload are shown in Fig. 10.

Fig. 10 shows that the hidden workload of the entire project increases with the increase in technical errors, which supports Hypothesis 7. Fig. 10 indicates that the hidden workload decreases with the increase in team experience, which supports Hypothesis 8. Fig. 10 shows that with the increase in position experience, the hidden workload of the entire project decreases, which supports Hypothesis 9.

5.3.4. Hypothesis testing of organizational structure

The degree of centralization, formalization, and matrixing of organization was adjusted to verify the hypotheses, and the simulation results of the relationship between them and the hidden workload are presented in Fig. 11.

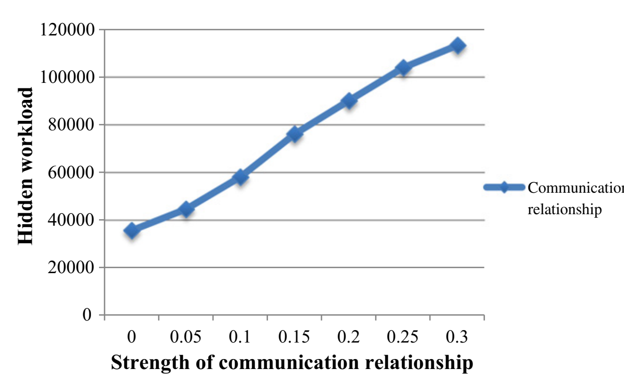

Fig. 8. Relationship between communication relationship and hidden workload.

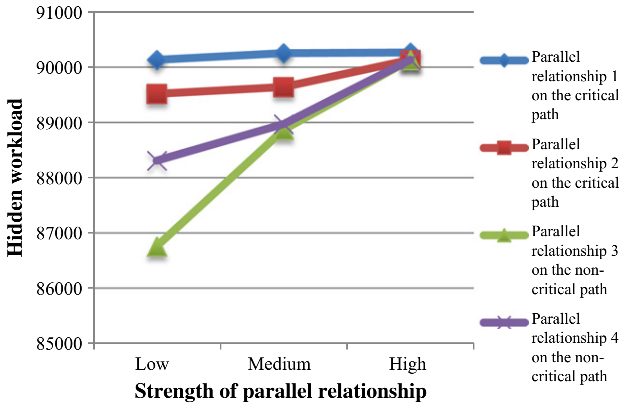

Fig. 9. Relationship between parallel relationship and hidden workload.

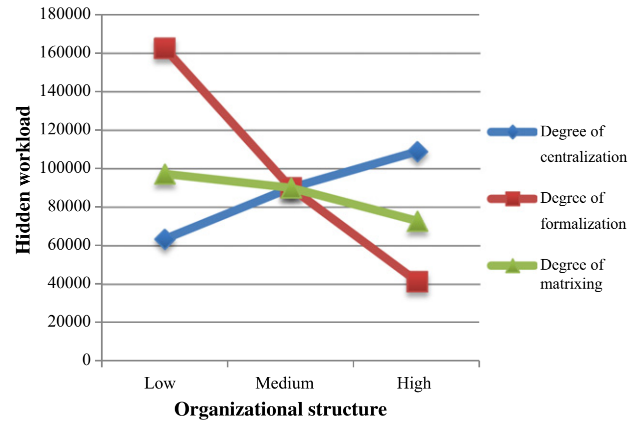

Fig. 11. Relationship between organizational structure and hidden workload.

Fig. 11 indicates that an increase in centralization resulted in an increase in the hidden workload of the entire project, which supports Hypothesis 10. Fig. 11 shows that an increase in formalization led to a decrease in the hidden workload of the entire project, which supports Hypothesis 11. Fig. 11 shows that the hidden workload of the entire project decreased when matrixing was increased, which supports Hypothesis 12.

All hypothesis testing confirmed that the 12 hypotheses were supported. Specifically, results of the testing showed that for task complexity, the higher the complexity of task and the relationship among tasks, the more hidden workload exists, whereas for organizational complexity, the higher the degree of centralization and technical errors, the higher the amount of hidden workload. By contrast, the higher the degrees of formalization and matrixing, the lesser the amount of hidden workload, and the more team and position experiences, the lesser the amount of hidden workload.

The literature review shows a relationship between these measures and project complexity. Thus, one can conclude that the higher the amount of hidden workload, the higher the amount of project workload, and vice versa. Project complexity can therefore be analyzed quantitatively using hidden workload, and the TO measure can be an effective tool for measurement.

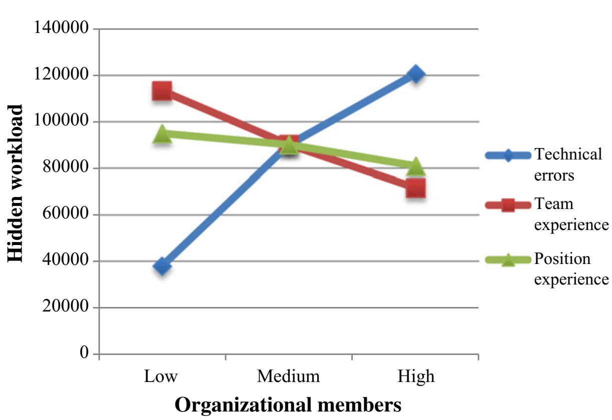

Fig. 10. Relationship between organizational members and hidden workload.

6. Conclusions

Managing project complexity has become an important aspect of project management of large-scale projects. However, existing methods to measure project complexity are often from static perspectives and do not reflect the dynamic and emerging nature of project complexity. This study proposed an effective method of measuring project complexity with hidden and direct works by modeling the dynamic emergence process. Compared with existing measures of project complexity, the TO measurement method provides a new perspective on project complexity as follows:

(1) Existing methods tend to use performance indicators as a type of measurement, such as project schedule, cost, and quality, which do not reflect the full nature of the project complexity. The TO measurement method addresses this limitation from the perspective of hidden workload, which is the result of project complexity and impact on project schedule, cost, quality, and other performance indicators indirectly.

(2) Existing measurement methods regard project complexity as a fixed value from the static view, which obviously neglects the natural attribute of project complexity-dynamism and emergence and causes difficulty in measuring project complexity. The ProjectSim model is one kind of organizational simulation model that can reflect the emergence process of project complexity; thus, the TO measurement method can reflect the dynamic nature of project complexity with hidden workload.

This study analyzed project complexity only from the TO perspective and did not consider elements outside the project such as environmental factors, thereby limiting the scope of our study. Hence, in the next stage of our study, more external influencing factors should be added into the model to provide a more comprehensive picture of project complexity.

Conflict of interest

There is no conflict of interest.

Acknowledgments

This study is supported by the National Natural Science Foundation of China (71390523 and 71471137). The authors would like to thank the editor and four anonymous reviewers for the insightful comments and suggestions on the earlier version of this paper.

References

Axtell, G., 2001. Teaching James's "The Will to Believe". Teach. Philos. 24 (4).

Baccarini, D., 1996. The concept of project complexity — a review. Int. J. Proj. Manag. 14 (4), 201–204.

Bosch-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., Verbraeck, A., 2011. Grasping project complexity in large engineering projects: the TOE (Technical, Organizational and Environmental) framework. Int. J. Proj. Manag. 29, 728–739.

Brockmann, C., Girmscheid, G., 2007. The inherent complexity of large scale engineering projects. Project Perspect. 22–26.

Carley, K., 1994. Sociology: computational organization theory. Soc. Sci. Comput. Rev. 12, 611–624.

Carley, K.M., 2002a. Computational organization science: a new frontier. PNAS 99 (3), 7257–7262 (www.pnas.org/cgi/doi/10.1073/pnas.082080599).

Carley, K.M., 2002b. Computational organizational science and organizational engineering. Simul. Model. Pract. Theory 253–269.

Chan, A.P.C., Scott, D., Chan, A.P.L., 2004. Factors affecting the success of a construction project. J. Constr. Eng. Manag. 130 (1), 153–155.

Chryssolouris, G., Dicke, K., Lee, M., 1994. An approach to real-time flexible scheduling. Int. J. Flex. Manuf. Syst. 6 (3), 235–253.

Cicmil, S., Williams, T., Thomas, J., Hodgson, D., 2006. Rethinking project management: researching the actuality of projects. Int. J. Proj. Manag. 24 (8), 675–686.

Cohen, G., Levitt, R.E., 1991. The virtual design team: an object-oriented model of information sharing in project design teams. Preparing for Construction in the 21st Century, pp. 348–353.

Corning, P.A., 1998. The synergism hypothesis: on the concept of synergy and its role in the evolution of complex systems. J. Soc. Evol. Syst. 21 (2), 133–172.

Expo Shanghai China, 2010. http://www.expo2010.cn/.

Frizelle, G., Woodcock, E., 1995. Measuring complexity as an aid to developing operational strategy. Int. J. Oper. Prod. Manage. 15 (5), 26–39.

Geraldi, J., Adlbrecht, G., 2007. On faith, fact and interaction in projects. Proj. Manag. J. 38 (1), 32–43.

Geraldi, J., Maylor, H., Williams, T., 2011. Now, let's make it really complex (complicated): a systematic review of the complexities of projects. Int. J. Oper. Prod. Manage. 31 (9), 966–990.

Gidado, K., 1996. Project complexity: the focal point of construction production planning. Constr. Manage. Econ. 14 (3), 213–225.

Giezen, M., 2012. Keeping it simple? A case study into the advantages and disadvantages of reducing complexity in mega project planning. Int. J. Proj. Manag. 30 (7), 781–790.

Girmscheid, G., Brockmann, C., 2008. The inherent complexity of large scale engineering projects. Project Perspectives, Annual Publication of International Project Management Association, pp. 22–26.

Gransberg, D.D., Shane, J.S., Strong, K., del Puerto, C.L., 2012. Project complexity mapping in five dimensions for complex transportation projects. J. Manag. Eng. 29 (4), 316–326.

Harty, C., Goodier, C.I., Soetanto, R., Austin, S., Dainty, A.R.J., Price, A.D.F., 2007. The futures of construction: a critical review of construction future studies. Constr. Manage. Econ. 25 (5), 477–493.

He, Q., Luo, L., Hu, Y., Chan, A.P., 2014. Measuring the complexity of mega construction projects in China — a fuzzy analytic network process analysis. Int. J. Proj. Manag. http://dx.doi.org/10.1016/j.ijproman.2014.07.009.

Hu, Y., Chan, A.P.C., Le, Y., 2012. Conceptual framework of program organization for managing construction megaprojects — Chinese client's perspective. Working Paper Series, Proceedings of the Engineering Project Organization Conference, Rheden, Netherlands, July 10–12.

Hu, Y., Chan, A.P.C., Le, Y., 2014. Understanding determinants of program organization for construction megaprojects success — a Delphi survey of the Shanghai Expo construction. ASCE J. Manage. Eng. http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000310.

Ivory, C., Alderman, N., 2005. Can project management learn anything from studies of failure in complex systems? Proj. Manag. J. 36 (3), 5–16.

Kennedy, D.M., McComb, S.A., Vozdolska, R.R., 2011. An investigation of project complexity's influence on team communication using Monte Carlo simulation. J. Eng. Technol. Manag. 28, 109–127.

Lebcir, M., Choudrie, J., 2011. A dynamic model of the effects of project complexity on time to complete construction projects. Int. J. Innov. Manage. Technol. 2 (6), 477–483.

Lessard, D., Sakhrani, V., Miller, R., 2013. House of project complexity — understanding complexity in large infrastructure projects. Engineering Project Organization Conference, Devil's Thumb Ranch, 9–11 July 2013, Colorado.

Levitt, R., 2012a. Using simulation to study, design and invent organizations. J. Org. Des. 1 (3), 58–63.

Levitt, R.E., 2012b. The virtual design team: designing project organizations as engineers design bridges. J. Org. Des. 1 (2), 14–41.

Li, H., Yang, N.D., Guo, X., 2009. Research on the structure of the complexity of complex project system. Soft Sci. 23 (2), 75–79 (in Chinese).

Little, T.D., 1997. Mean and covariance structures (MACS) analyses of cross-cultural data: practical and theoretical issues. Multivar. Behav. Res. 32 (1), 53–76.

Lu, Y.B., Zhang, X., Gu, Z.M., 2010. Computational project organization and process under micro-contingency organization perspective and its application. Ind. Eng. Manage. 15 (4), 98–103 (in Chinese).

Lu, Y.B., Zhang, X., Wang, H.L., Gu, Z.M., 2013. Agent based computational project organization and process model. Syst. Eng. Theory Pract. 33 (5), 1225–1230 (in Chinese).

Maylor, H., 2003. Project Management. 3rd ed. FT Prentice Hall, Harlow, UK.

Maylor, H., Vidgen, R., Carver, S., 2008. Managerial complexity in project-based operations: a grounded model and its implications for practice. Proj. Manag. J. 39, 15–26.

Owens, J., Ahn, J., Shane, J.S., Strong, K.C., Gransberg, D.D., 2012. Defining complex project management of large US transportation projects: a comparative case study analysis. Public Works Manage. Policy 17 (2), 170–188.

Prietula, M., Carley, K., Gasser, L., 1998. Simulating Organizations: Computational Models of Institutions and Groups. AAAI/MIT Press, Cambridge, MA.

Remington, K., Pollack, J., 2007. Tools for Complex Projects. Gower Publishing Company, Aldershot, UK.

Remington, K., Zolin, R., Turner, R., 2009. A model of project complexity: distinguishing dimensions of complexity from severity. Proceedings of the 9th International Research Network of Project Management Conference, 11–13 October 2009, Berlin.

Sargent, R.G., 1992. Validation and verification of simulation models. Proceedings of 1992 Winter Simulation Conference.

Senescu, R.R., Aranda-Mena, G., Haymaker, J.R., 2012. Relationships between project complexity and communication. J. Manag. Eng. 29 (2), 183–197.

Shafiei-Monfared, S., Jenab, K., 2012. A novel approach for complexity measure analysis in design projects. J. Eng. Des. 23 (3), 185–194.

Shanghai Expo Construction Headquarters (SECH) Office, 2008. The Outlines of Shanghai Expo Construction, Shanghai, China (in Chinese).

Shanghai Expo Construction Headquarters (SECH) Office, 2009. The Outlines of Shanghai Expo Construction, Shanghai, China (in Chinese).

Sinha, S., Kumar, B., Thomson, A., 2006. Measuring project complexity: a project manager's tool. Archit. Eng. Des. Manage. 2 (3), 187–202.

Taikonda, M.V., Rosenthal, S.R., 2000. Technology, novelty, project complexity and product development project execution success: a deeper look at task uncertainty in product innovation. IEEE Trans. Eng. Manag. 47 (1), 74–87.

Thomas, J., Mengel, T., 2008. Preparing project managers to deal with complexity — advanced project management education. Int. J. Proj. Manag. 26, 304–315.

Thompson, J.D., 1967. Organizations in Action.

Turner, J.R., Cochrane, R.A., 1993. Goals-and-methods matrix: coping with projects with ill defined goals and/or methods of achieving them. Int. J. Proj. Manag. 11 (2), 93–102.

Vidal, L.A., Marle, F., 2008. Understanding project complexity: implications on project management. Kybernetes 37 (8), 1094–1110.

Vidal, L.A., Marle, F., Bocquet, J.C., 2010. Using a Delphi process and the Analytic Hierarchy Process (AHP) to evaluate the complexity of projects. Expert Systems with Applications 38, 5388–5405.

Vidal, L.A., Marle, F., Bocquet, J.C., 2011. Measuring project complexity using the Analytic Hierarchy Process. Int. J. Proj. Manag. 29, 718–727.

Wiendahl, H.P., Scholtissek, P., 1994. Management and control of complexity in manufacturing. Manuf. Technol. 43 (2), 533–540.

Williams, T.M., 1999. The need for new paradigms for complex projects. Int. J. Proj. Manag. 17 (5), 269–273.

Wood, H., Ashton, P., 2010. The factors of project complexity. TG62 — Special Track 18th CIB World Building Congress, May 2010 Salford, United Kingdom.

World Bank, 2010. The Little Green Data Book. World Bank, Washington.

Xia, B., Chan, A.P.C., 2012. Measuring complexity for building projects: a Delphi study. Eng. Constr. Archit. Manag. 19 (1), 7–24.

Xia, W., Lee, G., 2004. Grasping the complexity of IS development projects. Commun. ACM 47 (5), 68–74.

Yan, J., Levitt, R.E., 1996. The virtual design team: a computational model of project organizations. Comput. Math. Org. Theory 2 (3), 171–196.