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Developing a city-level multi-project management information system for Chinese urbanization

Yongkui Li [a], Yujie Lu [b,*], Young Hoon Kwak [c], Shuang Dong [a]

[a] *School of Economics and Management, Tongji University, China*
[b] *Department of Building, School of Design and Environment, National University of Singapore, Singapore*
[c] *Department of Decision Sciences, School of Business, The George Washington University, Washington, DC 20052, USA*

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Abstract

The unprecedented Chinese urbanization leads to massive government-funded construction projects. In most cities, a special project management mode called "Agent Construction Model (ACM)" has been adopted to manage and govern these projects under the same umbrella of administrative standards. The ACM integrates all available government resources to complete the urbanization projects but meanwhile it faces great challenges from overwhelming complex information and information processing. This study presents the development of a city-level multi-project management information system to decompose the information processing complexity in the context of ACM management mode. The complex adaptive system and two specific development techniques—adaptive project framework and modularized functional design method—are introduced for the system development. The system was validated at a typical urbanization city in Changchun, China. This research complements the existing project information system by adopting complexity design principles and it also provides practical value for managing large-scale urbanization projects.

Keywords: Urbanization; Multi-project; Complexity; Case study; Project management information system

1. Introduction

1.1. Background of Chinese urbanization and project management models

China is experiencing the largest expansion of urbanization ever in its history, where the urbanization ratio increased from 36.22% to 52.57% in 2000 to 2013, with an estimation of 60% in 2020 (Pan and Wei, 2013). Nationwide urbanization brings massive infrastructure and construction projects in all geographical areas. Since 1992, China, on average, invested 8.5% of its Gross Domestic Product into infrastructure and construction industry, far exceeding any other countries in the world. In terms of monetary value, annual spending of Chinese infrastructure and construction now surpasses the United States and the European Union (Chen et al., 2013). Between 1997 and 2007, over 80% of the project funds came from government supported or related subsidies (Wang et al., 2011) where majority of infrastructure projects are funded by state-owned investment entities and corporations. Under the leadership and generous support of the government, enormous achievements have been achieved in the infrastructure and construction industry, making China as one of the top countries with the longest railways, highways, and high-speed rails.

Due to particular economic regime and market attributes in China, those large-scale infrastructure projects used to have three procurement system for construction: self-build model, government construction commanding unit model, and state-owned construction enterprises model. Such methods can successfully run particular types of project based on investment entity, project

* Corresponding author at: SDE1-03-05, Department of Building, 4 Architecture Drive, Singapore 117566, Singapore. Tel.: +65 6516 5894.
E-mail address: luy@nus.edu.sg (Y. Lu).

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location, level of authority, and other administrative reasons. However, a series of problems have also been reported (Lu et al., 2011), such as budget overrun from project scope creep by administrative decision makers, poor quality due to limited professional construction management service, and misconduct and corruptions owning to rent-seeking of administrative relationships.

In 2004, State Council of China issued the "Regulation on Reforming the Government Investment System" to encourage a new project management mode, Agent Construction Model (ACM) or in Chinese "Dai Jian Zhi", for all not-for-profit projects in an effort to improve the effectiveness and efficiency of infrastructure construction management. The ACM is a management model of delivering construction projects by means of consigning the project to specialized engineering management organization that is called agent owner, who is familiar to laws, regulations, and construction procurements (Hou, 2003). The appointed ACM firm is expected to manage the project's construction process effectively and deliver the completed project to end-users within project's cost, time, and specification (The State Council of China, 2004).

In practice, two ACM systems have been emerged: market-based ACM and government-based ACM (Bing et al., 2005; Shen et al., 2006). Market-based ACM appoints the construction project management services to a private firm via market bidding and tendering process. Such process takes advantage of competing market to select the most qualified agent to manage the project. Compared to the market-based ACM, the government-based ACM is more administrative oriented. In such model, the government establishes a specialized management unit called *ACM center*, as an official unit belonging to the department of urban and rural construction of each municipality. The ACM center manages the construction process of all public-invested projects across different departments, such as public school facilities, courts, and fire stations. With the support of the government, the ACM center can apply the administrative power and authorities to assembly the resources needed by the projects and to run those "thorny" projects.

Due to the direct financial and administrative support by the government, the ACM center has advantages of centralized planning, coordination, and resource allocation, thus considerably improve the project management efficiency and reduce the management cost (Yin et al., 2010). The ACM center remains organizationally stable for a longer duration and is more reliable in applying project management principles for most public construction projects (Bing et al., 2005; Shen et al., 2006; Wu et al., 2012; Yan and Zhou, 2009). As a result, the ACM center became a popular project management method for Chinese government-invested project. This study will focus on the ACM center as the context of Chinese project management mode for all city-level infrastructure renewal projects.

One should note that the ACM center is originally developed from the Construction Manager (CM) (Yin et al., 2010) but show differences from CM in following three perspectives. First, the ACM center is a more integrated entity by managing multiple projects for various project owners at the same time rather than CM. For instance, the ACM center of a typical Chinese city manages hundreds of public projects simultaneously, such as educational facilities, roads, and bridges; while the CM is mainly focused on managing one single project at a time. Second, the ACM center is a government agency and also only manages government invested projects (Gao and Zhu, 2006). This brings special considerations since those projects are not only bounded with economic targets but also involved with social issues and various stakeholders. Especially in the urbanization process when most of projects are built on existing facilities, management of those projects need extensively coordination and support from local communities. But CM is primarily used for "for-profit" clients and contractors with less social considerations. Third, the responsibilities of the ACM center are different from CM. The ACM does not charge for the maximum grantee price (as in the CM "at risk") but in most cases is required to complete the projects within a strict time and budget set by its client, typically the government. These differences highlight the ACM center as a special project management model for Chinese urbanization.

2. Research needs and significance

Although above numerous special advantages of the ACM center, the overwhelming expansion of urbanization has caused great challenges and problems for the government centralized management system. For example, the ACM center needs plan and construct various types of complex projects, from bridges, transportation hubs, to hospitals, under tight schedule and intertwined management scopes. It is also difficult to coordinate and manage hundreds of projects and thousands of participants simultaneously from diversified industries with different requirements and fragmented information pieces. As projects become more complex, the amount and the level of information details related to the ACM center increase that makes the process of storing, retrieving and analyzing the control information more complicated (Ruwanpura et al., 2012). In addition, the variability and uncertainty of external environment commonly lead to delayed decisions. All of the above issues call for advanced information management solutions and decision-making support systems.

Existing practices show that multi-project information management system can integrate the fragmented information in the decentralized environment, promote the effectiveness of communication and coordination, process complex project information, and enhance managerial performance at project, program, and portfolio (Bekkers, 2007; Froese, 2010; Halfawy, 2010; Han et al., 2009; Park and Ryoo, 2008; Zeng et al., 2012). Current project management information system software, such as Oracle Primavera P6, can provide solutions to detect latent issues before they occur, meet schedule deadlines, and easily collaborate. However, most of them are not capable of managing multi-project (Raymond and Bergeron, 2008), and also show less suitable for the ACM center which require cross-organizational coordination, integrated process management for investment, contract and budget, and ad-hoc customized functions. These limited options do not be address and handle the complexity and sizes of enormous Chinese construction projects, particularly in relation to the ACM center procurement system. A typical city-level ACM center manages more than two hundred public infrastructure projects yearly. Considering such a large volume of projects, existing systems have great limitations. The main issue would be how to effectively manage, share, and coordinate the complex information that is generated from hundreds of infrastructure projects. Therefore, a new comprehensive integration information system with advanced features like cross-organization user management, multi-project integration control, life-cycle decision support, and complex information processing is needed for multi-project management and control.

This study aims to help the ACM decision makers efficiently manage the complex information for simultaneously constructing multiple infrastructure projects. In particular, research tries to address the followings: 1) figure out the sources of complexity in this urbanization construction process; 2) design an information system to improve the information processing efficiency during information coordination, communication, exchange processes; and 3) test and validate the developed information system and its benefits.

The organization of the paper is as follows. Section 3 explores the complexity of managing and controlling large-size infrastructure construction projects, in particular, the perspective of the ACM center. Section 4 uses a case in Changchun, China to elaborate the real complexity in the multi-project environment by considering the case background, organizational structures, governance, complexity factors and strategies. Section 5 analyzes the information system functions in terms of the user's requirement, process requirement, and information requirement. Section 6 presents the design and development method for complexity-based information system, including using adaptive project framework, agile modularized design, and system architecture design. Section 7 evaluates the system per-deployment results. The last section summarizes the findings and provides suggestions for future study.

This research will assist the government for improving the communication efficiency, coordination and integrated control performance, and also provide a system development framework to similar urbanization projects. Although the study background is based on Chinese urbanization, the system development philosophy and methodology can be applied to any global management environment that faces multi-project and complex contexts. The development of this system provides innovative methodology and system platform that contributes to the body of knowledge of project management information system and to the multi-project management practices of the similar projects in the future.

3. The complexity of managing and controlling City-Level Infrastructure Projects (CLIPs)

3.1. The complexity of CLIPs

Existing complexity theory suggests various ways to categorize the complexity of a project. Baccarini (1996) divided project complexity into two dimensions based on the sources of complexity: organizational complexity which includes the number of hierarchies, companies and departments, and technological complexity which includes operational, material and knowledge characteristics. Bosch-Rekveldt et al. (2011) proposed three classifications: 1) technological complexity including goal, range, mission, experience and risk, 2) organizational complexity including scale, resource, project team, commitment, and risk, and 3) environmental complexity including stakeholders, market, and risk. Remington and Pollack (2007) proposed a four-type project complexity as useful categories for analysis: structural complexity, technical complexity, directional complexity, and temporal complexity. Girmscheid and Brockmann (2008) divided complexity into five groups: task complexity, societal complexity, cultural complexity, operational complexity, and cognitive complexity.

CLIPs are usually a combination of complex and large-scaled projects, such as highway intersections, mass-transit interchange hubs, and high-speed rails. Compared to a single project, CLIPs show highly complex due to the system interconnections among projects. Shane et al. (2012) discussed the sources of complexity of US and international large transportation projects from five project aspects (cost, schedule, design, context, and finance), and indicated the reciprocal and intertwined factors among these aspects make projects more complex. Hertogh and Westerveld (2010) decomposed the complexity of the large infrastructure projects into six dimensions as social, financial, organizational, legal, technical and time complexity. They also argued that the scientific perception of complexity should consist of two perspectives: detail complexity and dynamic complexity. Favari (2012) analyzed the complexity of urban infrastructure projects and found that both project's internal complexity and external environment complexity affects the complexity of managing infrastructure. This research also identified five key factors to determine the complexity including effective sponsorship, organizational network analysis, communication management, contract management, and risk management. This research summarizes the complexity of urban infrastructure projects in Table 1 which was based on the research of Hertogh and Westerveld (2010).

In addition to the fact that infrastructure is a multi-project system, the ACM could even be more complex because it manages projects, programs and even portfolios. A typical ACM center is responsible to build a combination of projects, from a single project like hospital, to multi-project like metro railway and stations. For such highly complex project system, traditional project management theories, methods, and technologies are not enough to satisfy all the needs and requirements (Hass, 2009). Researchers suggested exploring innovative management approach for the complex multi-project problem (Winter et al., 2006), particularly from the science of complexity theory.

The classic characteristics of complexity theory treat the system as the complex adaptive system (CAS). Aritua et al. (2009) used CAS theory to analyze six attributes of the complex multi-project management: inter-relationships, adaptability, self-organization, emergence, feedback, and non-linearity. In addition to these arguments which can be applied similarly to the

Table 1
The complexity of urban infrastructure projects (adapted from Hertogh and Westerveld, 2010).

Dimensions	Complexity factors
Social complexity	• Conflict of interest caused by multiple project stakeholders • Different meanings and perceptions caused by large numbers of project participants • Widespread impact on urban environment, transportation, local society, industrial production etc. • Complex relationships including formal and informal connections
Financial complexity	• Various investment sources, including tax, appropriation, loan, bond and private capital • Inconsistent and changing financial requirements, and difficulty of determining project's cost objects • Strategic misinterpretation, optimism bias and pessimism bias • 'Cascade of distortion', that is cost information distortion caused by the transmission through different management levels, leading to the wrong decision
Organizational complexity	• Large-scale project organizations, complex organizational structures of projects, programs and portfolios • Complex organization relationships, blurred interfaces, numerous contracts need to be arranged, and complex contractual relationships • Temporary organizations with frequently changing contractors, designers, and suppliers • Multiple organization levels, long chains of communication, complex communication relationships • The appropriateness between project organizations (or project managers) and project tasks
Legal complexity	• Vacancy or immature laws and regulations, mutual conflicts between different laws and regulations, lack of specific regulations or codes to support Agent Construction Model (ACM) delivery • Influences from the existing laws and regulations, especially from the new issued laws, such as the property protection by the new construction demolition regulation • The inconsistency between regulatory requirements and reality, especially in the special and emergency situations
Technical complexity	• Technical uncertainty, especially for the underground construction and extreme weather conditions • Technology applications influenced by personnel skills and capacities • Unproven technologies or controllability of technology induced complexity
Time complexity	• The tight schedule of urbanization, huge pressures from governmental and societal expectations • The changes of project objectives and plans caused by enormous factors, such as funds and demolition of existing buildings • Large numbers of concurrent tasks

complexity of CLIPs practices, the paper extends the analysis of six CAS attributes for CLIPs as below:

(1) Inter-relationships. CLIPs are connected or related in broad ways in the context of ACM management and control, such as investment sources, project types, and locations. Project stakeholders including the government, investors, ACM center, designers, contractors, and suppliers are closely tied with one another influencing each other.
(2) Adaptability. CLIPs are open systems in terms of its socio and functional influences and exchange from the project external environment. CLIPs continuously absorb new information and adjust their behaviors accordingly for substantial reasons, such as administrative decisions, macro-economic and political uncertainty, updated project functional requirements, and the movement or contest of nearby citizens.
(3) Self-organization. The ACM is in its infant phase (Hu et al., 2006; Yan and Zhou, 2009) and shows great potential of self-growing toward more organized structure.
(4) Emergence. Different combinations of the multi-project could lead to entirely different project performance, either better or worse than the expectation. When hundreds of construction projects are undertaken by thousands of construction participants, enormous unexpectations emerge, such as hidden workloads and reworks for conflict projects, redundant communication information, and intensive coordination due to information asymmetry (Dietrich, 2007; Love and Irani, 2004). These emerged unexpected consequences in most cases lower the work productivity and thus bring considerable challenges to the construction management and control.
(5) Feedback. The openness and dynamics of infrastructure projects require project managers to receive feedbacks outside the infrastructure system, and adapt to the management. Due to vast numbers of parties, timely transferring and processing the information becomes very important within all relevant parties to improve the management efficiency and project delivery.
(6) Non-linearity. Due to the impact of openness, organization, and interrelationship rooted in the CLIPs, trivial incidences in the initial conditions or external environment cause large and unpredictable consequences in the outcomes of the system, such as project schedule failure and cost overrun.

3.2. The complexity of CLIPs control and management

CLIPs are a complex system that incorporates complex theory, science, methods, and tools. Hertogh and Westerveld (2010) proposed four approaches to manage the complexity in large-scale infrastructure (shown in Fig. 1). This four-dimension quadrant provides essential foundation for the analysis of complexity CLIPs management and strategies as follows:

Internal and content focus approach relies on a pure focus in finding a technical solution to a perceived problem without many attentions for strategies and interaction (Hertogh and Westerveld, 2010). Systems management strategies focus on control, including decomposition for organization, time, costs, quality and risks. In multi-project, project managers handling different projects with different scopes, complexities, and timelines face particular problems (Maylor et al., 2006).

Interactive management strategies focus on interaction, including alignment, redefinition of the problem and change of scope, using short-term predictability, and variation. In multi-project, managers deal with interdependencies and interactions among projects, but have few tools and techniques available to help them oversee the whole picture of all interdependencies and interactions (Patanakul and Milosevic, 2008). Dynamic management strategies balance control and interaction, including balancing the organization structure, strategies of control and interaction over time (Hertogh and Westerveld, 2010).

The integration of above strategies and methods are indispensable for the CLIPs complexity management and control since any single approach has limited effects. An effective CLIPs management requires synergistic approaches that are built upon the complexity attributes of CLIPs, complex adaptive system, and corresponding strategies. The following section introduces Changchun, a city of China, as a case study to discuss the process of the design, development, and implementation of the multi-project integrated management and control system. The process of case study is described in Fig. 2.

4. Case study of urbanization in the City of Changchun

4.1. Case background

Changchun is the capital of Jilin Province, located in the northeast of China. It has an area about 20,000 km^2 with population of 7.6 million in the year 2010. The city's strategic development plan forecasts the population will reach 14 million in the long-term according to urbanization transformation and inflow of rural workforces. The winter of Changchun is long, cold, and windy with lowest temperature of −27 °F, due to the influence of the Siberian anticyclone. The annual frost period is around 200 days and thus the suitable construction period is only between May and October.

In 2007, the city government established the Changchun ACM center, an administrative affiliate to the governmental Urban and Rural Construction Committee. The ACM center's responsibility is to provide professional project management services for all government-invested projects, or named public projects. The organization of the ACM center follows the matrix organization structure, with project lines and functional department intersecting each other. The relationships between ACM center and relevant project participants are shown in Fig. 3.

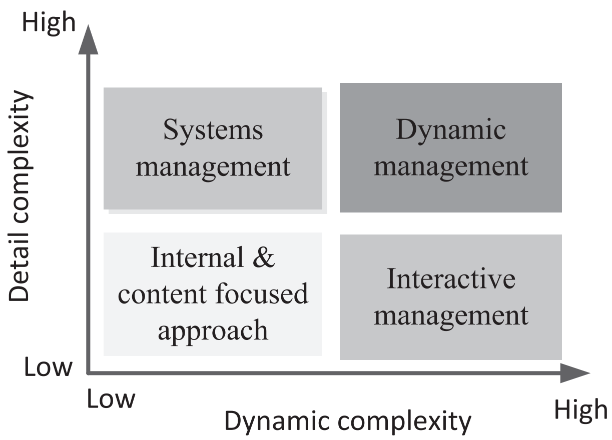

Fig. 1. Four strategies to manage the project complexity (adapted from Aritua et al., 2009).

The primary duties of the ACM center include: (1) manage and control the construction process of all public projects according to the authorized scope delegated by the municipal government to ensure the project completion is on time, on budget, and meets the expected specification; (2) supervise all public projects' outcomes and construction activities based on administrative standard and regulations, and comply with relevant laws and regulations; and (3) coordinate public projects' front–end planning and construction process with potential and relevant participants to keep the project workable.

Due to Changchun's fast urbanization speed, the numbers of public projects have increased dramatically since 2009 as a result of generous infrastructure stimulus investment from both central and local administrations. In 2010 alone, Changchun launched over 220 public projects with total investment over 20 billion RMB (equivalent of 3.3 billion USD, given the exchange rate of RMB to USD is 0.1634). Such large numbers and scales of public projects brought tremendous challenges to the ACM center in terms of workloads and management efficiency. In order to address these issues and improve work performance, the ACM center decided to develop and use web-based program management system to manage and control all public projects.

4.2. The complexity context

The ACM center is committed to manage two categories of public projects, buildings and infrastructures. Buildings include public housings and facilities, such as hospitals, courthouse, and prisons. Infrastructures include city roads, bridges, railway stations, drainage and others but excluding metro, waterways, state highways, and gardens which belong to another separate government agencies. These public projects are complex in terms of their number of characteristics, scales, varying project types, construction periods, locations funded entities, end-users, etc. The summarized complex attributes of public projects, as well as associated complexity management and strategies are discussed in Table 2.

4.3. Data collection

The date used in this study was collected from the ACM center via field trips, interview, survey, and project meetings. The authors have been intensively involved with the ACM center for the CLIPs management consulting since 2009. The collected data covers all aspects of ACM working operations, including its organizational structure and responsibilities, management objectives, principles and expectations, business processes, information exchange, and collaboration patterns. The data formats include documented project data, meeting minutes, official announcements, management decisions, and internal standards and codes. During the data collection period, the author also observed the onsite daily operations and

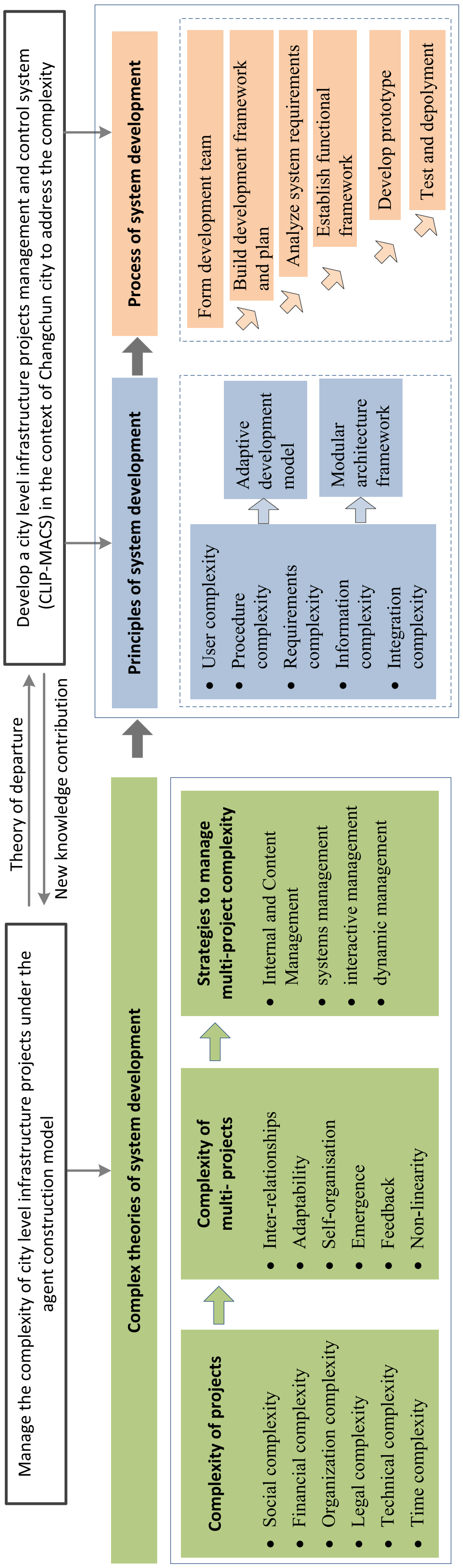

Fig. 2. The overall process of case study and the development of CLIP-MACS.

interviewed a variety of project participants, such as executive managers, functional managers, project managers, leaders and directors, and local government officials.

5. Functional and users requirements analysis of CLIPs-Management and Control System (CLIPs-MACS)

Functional requirement is essential for the success of system development project. Historical lessons show that seven out of eight IT projects were delivered as failures or underperformed (McManus and Wood-Harper, 2007). Two primary factors causing failures in systems development are both related with functional requirements and realization, which are (a) requirements uncertainty in software development, and (b) interpersonal conflicts between users and information system professionals throughout the entire system project (Liu et al., 2011). In particular, the complex system development requires additional attentions for the system requirement including the requirement analysis, requirement definition, and requirement change management than managing a single project.

5.1. Organizational mechanism

Existing literature shows that as the level of uncertainty regarding user requirements increases, the system development should move away from the traditional waterfall life-cycle model and toward more evolutionary approaches with heavy stakeholder involvement (Selden and Moynihan, 2000). In other words, the effective communication and collaboration between end-users and software developers show crucial effect for complex system development. This ideal communication, however, is missing from the practices where either end-users are unable to express what they want, or developer misunderstands users' requirements. Such poor communication will eventually lead to requirement uncertainty and result in escalation of management complexity.

Given the suggestions from Wysocki (2011) and Hass (2009), the best way to reduce the uncertainties of functional requirements is through close cooperation between the business stakeholders and technicians, between users and developer, and between functional and project departments. The adaptive methods for defining, expressing, and analyzing the requirements are therefore transformed into iterative, visualized, and test-driven process. To ensure the software functions matching with the practical requirements, this study builds an integrated system development team (ISDT) consisting of three parties: the client (also as the software end-users), project management consultants, and IT software developers. The client signed consulting contract with the project management consultants to provide system requirement analysis and high-level system architecture, and signed system development contract with local IT software developer for system coding and delivery. The project management consultants are responsible to ensure the system functions and usability be realized in time, cost, and quality. The working scope for project management consultants include requirement analysis, requirement definition, requirement change control, and key point requirement re-investigation.

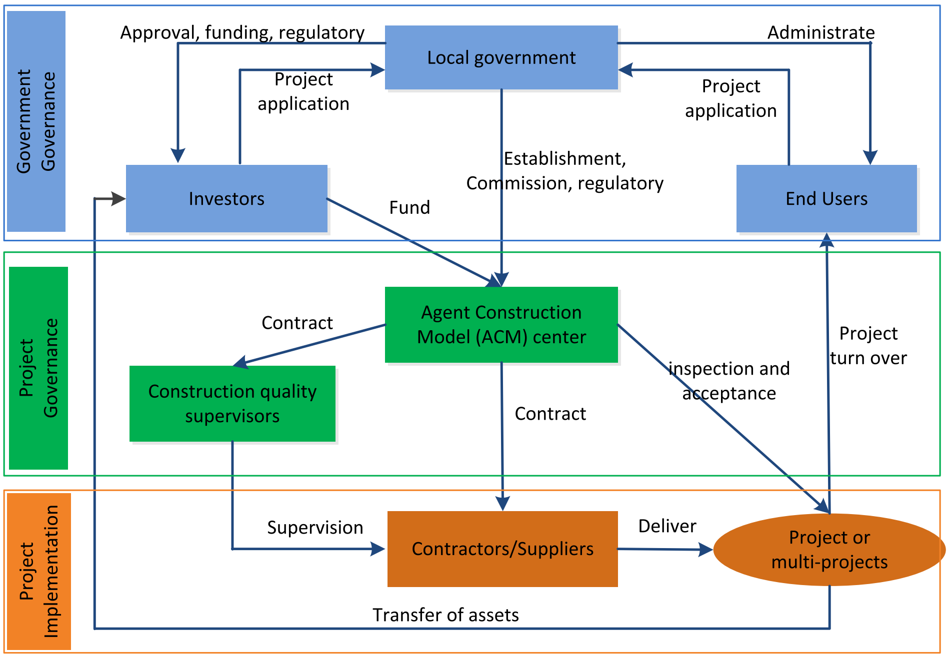

Fig. 3. Project governance structure for Changchun public multi-project construction.

5.2. User's requirements analysis

For every project, the ACM center manages project life-cycle phases from initiation to completion, including project approval, geotechnical survey, contract bidding and tendering, architecture and construction design, field construction, and project transfer. These management and control functions, performed independently, are yet closely related with each other cohesively to move projects forward.

The management functionality of the ACM center also decides its intensive interactions with a broad of relevant departments, including both internal and external ones, than traditional projects. The internal ACM center consists of two parts: functional department and project department. In addition, the ACM center largely works with external project stakeholders, such as administrative regulators, investment entities, compulsory quality supervision, and general and sub-contractors. These users are divided into three levels: management engineers, department managers, and decision-making leaders due to their different roles and accessibility in the CLIPs-MACS.

The key source of complexity for integration system development comes from understanding and interpreting organizational and users' requirements. Variable user requirement and complex system function design need a co-evolutionary adaptation approach in which users and system experts need intensive collaboration to cope with future demands which is uncertain, variable, and diversified. ISDT works collaboratively for the demand identification, forecasting, and control. While PM consultants and IT software developer were joint responsible for the demand collection, interpretation and analysis, as well as manage the development process; the ISDT confirmed the development milestones and overall functional framework.

This study uses the following procedures to refine users' functional requirements of CLIPs-MACS. First, the ISDT outlined the common features of the system based on existing literature, project related achieves and documents, and similar systems, such as Microsoft Enterprise Project Management (Braglia and Frosolini, 2014; Caniëls and Bakens, 2012; Halfawy, 2010). Second, face-to-face interviews with specialists and end-users were performed to specify particular features and functions of the system. The interview process was managed by the project management consultants. The invited interviewees included project organization experts and end-users, complex system experts, top-level decision makers from the client's organization, and senior system architecture engineers. The interview results were then interpreted as a process flow to discuss the user requirements and to map all related functions. Third, when analyzing function requirements of CLIPs-MACS, this study put extra emphasis on the complexity management of multiple public projects in addition to the traditional project, portfolio, and program management.

The end-users' questionnaire of complexity management requirements is shown in Appendix 1, which is divided into three different user roles: decision makers, department and project managers, and engineers. This questionnaire shows special contribution to the system development and facilitates user's requirement analysis by labeling both complexity attributes (social, financial, organizational, legal, technical and time complexity) and CAS attributes (inter-relationships, adaptability, self-organization, emergence, feedback and non-linearity).

The analysis of users' requirements above determined the scopes of system work and function specification, which includes function description for both common and specific management requirements, user case definition and the relationship between users, roles and functions, standard process, data collection and reporting forms, and customized message alert. Meanwhile, the business process mapping for multiple project management was established to provide the basis for designing functional modules

Table 2
The complexity of multi-project and multi-project management in the Changchun urbanization.

Multi-project complexity			Multi-project complexity management	
Dimensions	Elements	Main factors	Coping strategies	Coping approaches
Attributes	Detail (including technical)	Large numbers, various types, wide distribution; technical complexity for certain projects	Internal & content focused approach	Project database; project repository; technical demonstration and approval
	Dynamic	Emergent projects or priority adjustments		
Objectives	Social	Top attentions from project stakeholders	Systems management, interactive management	Media communication; change management; multi-layer schedule management; contract management; cost management; process management; health, safety and environment management; integration system and platform support
	Financial	Difficulties in cost and investment management caused by uncertainties from management and multiple levels of organizations		
	Time	Pressures raised by extremely tight schedule and short notice, asynchronous construction periods including new, rebuild, expanded, and renovated projects at the same time		
Organization	Social	Multi-stakeholders; significant impacts on city operations and local citizens' life; possible corruptions in the construction bidding and tendering	Systems management, dynamic management	Multi-dimensional organization innovation; optimization of governance mechanisms; system design; standard contract design; optimization of contractual changes; supplier evaluation and shortlist; improvement of professional's skills; relying on professional team; integrated system supporting
	Financial	Multiple investors, and multiple sources of investment		
	Organizational	Complex relationships between external supervisions; large scale organizations; complex contractual relationships; frequent changes in contractors and suppliers; shortage of skilled professionals; inappropriateness between organizational positions and personnel skills		
Environment	Social	Highly open management systems, intensive interactions and interferences with social and urban operating systems	Dynamic management	Media communication; construction schedule optimization; management system design; risk assessment of new laws and regulations; innovative project financing models, such as Public Private Partnerships
	Legal	legislative inadequacies on Agent Construction Model (ACM); influence of new rules and regulations		
	Financial	Various sources of investment; impact of micro-economic development; impact of private capital involvement		

and processes, building data relationship and integration, and, managing involved roles and organizations. The designed user case for the system is shown in Fig. 4.

The system has been divided into three general modules: engineering management, collaboration management and program management, based on the working business in the real practice. Engineering management and collaboration management use frequent data exchange to keep the data updated and to provide essential information to program management for its integration, analysis, visualization, and decision making support. In addition, the program management provides other functions, such as customized integration and reporting, project performance benchmark, project issue report, tracking and solvency, earn warning alert and project risk management.

In each of the module, the user's authority and managerial scope is set as follows, (1) management engineers inside the ACM project and department divisions are key roles to initial a new work flow, to manage the information input and update, and to authorize the data editing and communication, during the project lifecycle process; (2) project managers and department managers confirm and update the integrated project information, and have authority to view, edit, and process the information inquires; (3) decision makers are primarily the directors and executives of the ACM and they can view and edit all information for three modules; (4) government supervisors mostly view the integrated project information to monitor, track, and advise the project progress, and also to coordinate possible issues; (5) external users, who manage the land acquisition, existing facility removal, professional consultancy, and construction contractors, are limited to input corresponding information. The above authority setting can effectively decompose the complexity of system functions and information, and distribute intertwined relationship for compounded tasks more effectively to the corresponding users.

5.3. Process and information integration

Information processing interacts closely with management processes (Le et al., 2012; Wu and Hsieh, 2012). Complicated interactions among projects, users, and information overload the multi-project environment. Information from thousands of participants and organizations using various information formats make the management difficult to acquire useful information. Fragmented data have a great influence not only on project management performance but also on the decision quality (Caniëls and Bakens, 2012; Wu et al., 2012). Caniëls and Bakens (2012) pointed out that in a multi-project context, the availability of higher quality information processed by project management information system could increase the working efficiency of project managers. Thus, to effectively manage and control multiple public projects, CLIPs-MACS is designed to deliver timely, accurate, and integrated information to support sound decision-makings.

Integrating, processing, and reporting information are critical functions of CLIPs-MACS and are also the basis of real-time project control and decision-making for managing projects. This study uses one example selected from CLIPs-MACS's gigantic functions to illustrate the information integration. Project investment management, financial management, and contract management are all independent functional departments but work interactively for every project. These three aspects are functionally separated but managerially connected in the business process. Le et al. (2012) and Luo et al. (2011) argued that the information exchange between financial control and contract management was tightly related. It is necessary to support the management of these two processes and their interactions through establishing the integration framework, defining the information flow between them, and using a specially developed computer program. The proposed strategy for decomposing the complexity of CLIPs-MACS is to match the multi-project level management process and exchange information for the process-based financial control, schedule-based contract payment control, and monetary-based capital raising and payments. The integrated process of planning, investment, contract, and financial management is shown in Fig. 5.

The structured decomposition is the basis for managing budget, contract, and financial statement. Since most infrastructure projects primarily rely on public funds or state-owned companies, the budget decomposition is broken down by the project planning, project portfolio and funding sources; the contract decomposition is based on the sub-contracting rules and contract types; and the financial decomposition follows the standard subject categories issued by the Chinese financial accounting standards board. Due to such various decomposition rules, project data is difficult to be

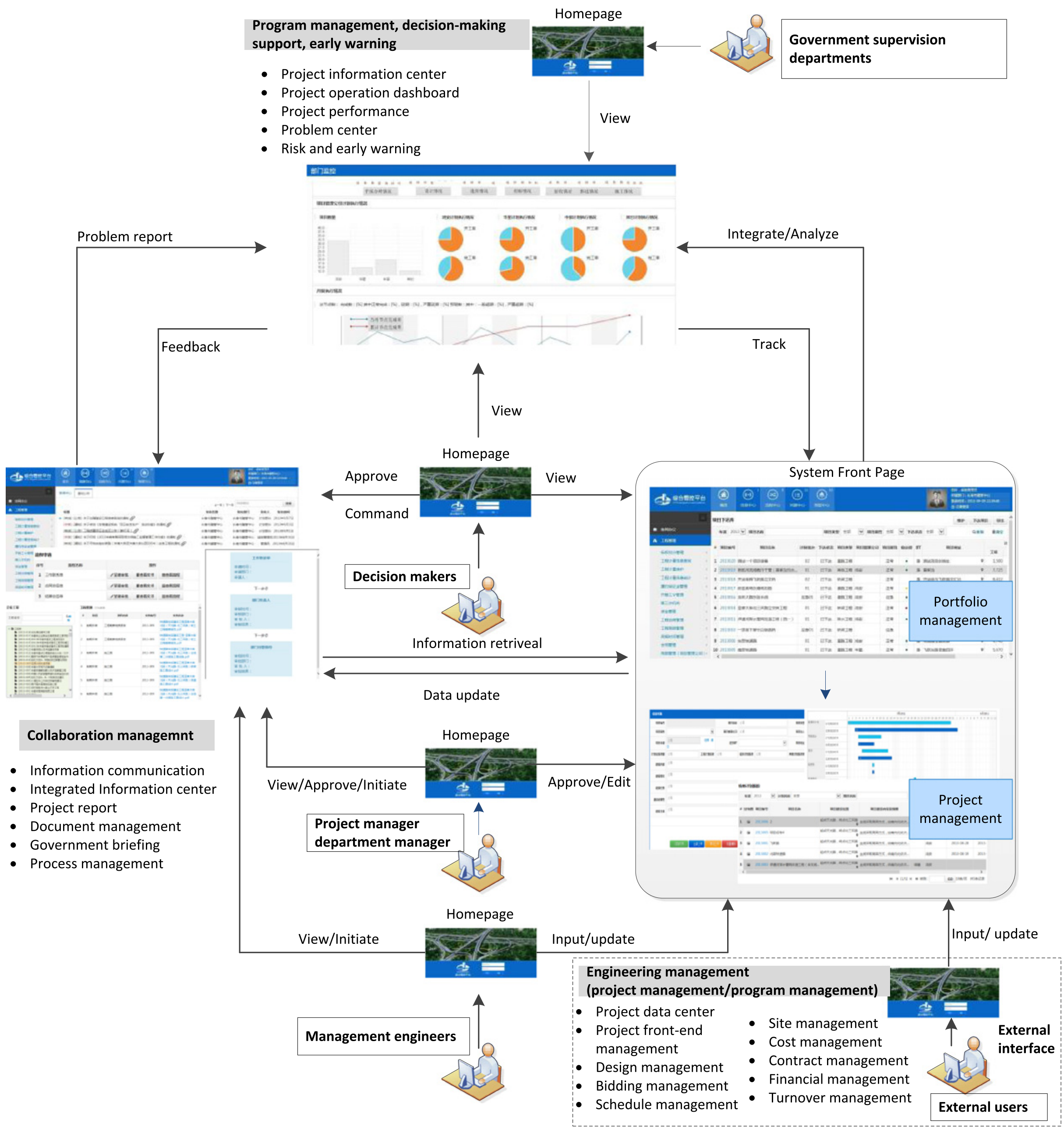

Fig. 4. The user case and functional modules' relationship in the CLIPs-MACS system.

matched. This research uses project breakdown structure (PBS) to decompose each project into small manageable units (SMU) and then apply the data analysis and data integration based on these SMU for managing budget, contract and financial reports. In addition, the data in different project lifecycle phases can be queued, processed, compared, and analyzed based on the project and managerial process, in order to achieve the integrated and dynamic information management. For instance, the financial reports can be transferred into actual realized investment data which can be used as reference to adjust future budget plans.

Information integration needs innovative support from the database. The CLIPs-MACS designed the structured data format, performed data correlation analysis, and built data integration model to ensure the efficiency and accuracy of information processing. When integrating investment management, contract management and finance management, enormous amount of data will be populated in the system. It is therefore pivotal to present these data to different levels of end-users depending on their levels, authorities, interests, and organizations. In addition, data structure was standardized considering the diversity of information attribute, types, contents, formats generated from multiple sources.

6. The design and development of CLIPs-MACS

6.1. Complexity-based design and development methods

The contemporary Information Systems Development (ISD) is generally acknowledged to be a complex activity (Kautz, 2012). Benbya and McKelvey (2006) presented a commendable analysis of sources of ISD complexity, which can be recognized as: changing user requirements, changing organizational needs, changing external competitive conditions, increased interdependencies among the involved individuals, organizations and technologies, and the rapid evolution of IS and IT. ISD can be viewed as a complex adaptive system (CAS) which can specify emergence mechanisms and characteristics, as well as react quickly and creatively to changing necessities. The application of CAS can make the complexity better understood. Alaa and Fitzgerald (2013) re-defined the agile information system development using CAS and emergencies in complexity. Based on the CAS theory, Benbya and McKelvey (2006) further suggested use an adaptive perspective to more effectively cope with the challenges of evolutionary complexity in changing environment and therefore propose seven principles for adaptive success of information system: (1) adaptive tension, (2) requisite complexity, (3) change rate, (4) modular design, (5) positive feedback, (6) causal intricacy, and (7) coordination rhythm.

CLIPs-MACS, as a multiple project integration information management system, is more complex than program information management system, portfolio information management system, or even the distributed information management system. CLIPs-MACS is a CAS-based development with unique attributes such as complex system functions, enormous users, uncertain system requirements, and open environment with external stakeholder. The complexity of CLIPs-MACS is not only embedded into the complex scope, distributed organizations, one-of-a-kind design, geographic distribution of project activities, strict time constraints, contingency risks, revenue-loss risks, but also shows as the dynamically changed and widely diversified user demands, quick on- and off-interim organizations and their relations, multiple administrative interfaces with land acquisition and approval agencies, overwhelming coordination with various agencies for removal and renewal of existing buildings and municipal facilities, last-minute emergent requested or changed projects, etc. Adaptation perspective of ISD that rests primarily on co-evolutionary theory will be much more useful for managing the emergent nature of such information systems than the prevailing traditional, top-down, engineering focused perspective (Alaa and Fitzgerald, 2013). In order to increase the success rate of system development and avoid frequent future changes, the system development call for advanced methods and techniques, including complex adaptive system development model, agile development framework, multi-level system technical architecture, and closely collaborative environment between users and ISDT.

6.2. Adaptive Project Framework (APF) development model

According to the project objectives and solutions, a broad project management methods can be adopted, such as agile project management (APM), extreme project management and Emertxe-project management (Wysocki, 2011). In the case of CLIPs-MACS, project complexity increases system requirements become highly uncertain and processes are expected to show numbers of iterations. Both software functional framework and technical solutions are likely to be changed continuously and therefore lead to high risk for the system development that requires new alternatives.

Adaptive Project Framework (APF) is an effective development method for complex system development (Wysocki, 2011). It is designed for projects where the goal is unclear and the solution is only partially known. APF is a customer-centered system development solution driven by customers that delivers timely feedback and frequent immediate results, continuously improves development, and approaches the ideal solutions with flexibility. The solutions of these projects are not completely known ahead-of-time and can only become known through doing the project (Wysocki, 2011). According to the APF development methodology, the project establishes the project development framework, work scope and project development cycle, customer checkpoints, and the pilot system version for the review test. In addition to the method framework, APF also represents a way of thinking about clients and how best to serve them.

Due to the constant change of system requirements and application context, all relevant software functions, the system architecture framework, and IT technical solutions change accordingly. The system's functional requirements are not able to be determined until the last minute of the system development, causing high risks of selecting proper system architecture and adopted IT solutions. To address this continuous change, the scope version management of APF is used, including milestone management, tracking changes, priority management, and conflict resolutions. The system development also applies the integrated development principles of iterative incremental prototype development and modular functional framework to mitigate the risks of system development.

To align with the adaptive development model, project organization uses a unique ISDT to implement the system development consists of clients (end-users), management and IT consulting firms, and local software development companies for the short-term system development and also for the long-term business partner to commercialize the future system product to potential market. Each member of ISDT shares both revenues and risks for the system development and pays much attention to both short-term and long-term success.

6.3. Modular functional framework

Modularization provides an effective way to decompose a complex information system into manageable modules by using splitting, organizing, and packaging the system functions. Each module contains a specific sub-function of a large system and keeps minimal interaction among one another. All modules are assembled into the whole system to satisfy the system's overall requirements and functions. Modularization can provide benefits to the information system development including increasing feasibility of product or component change, increasing product

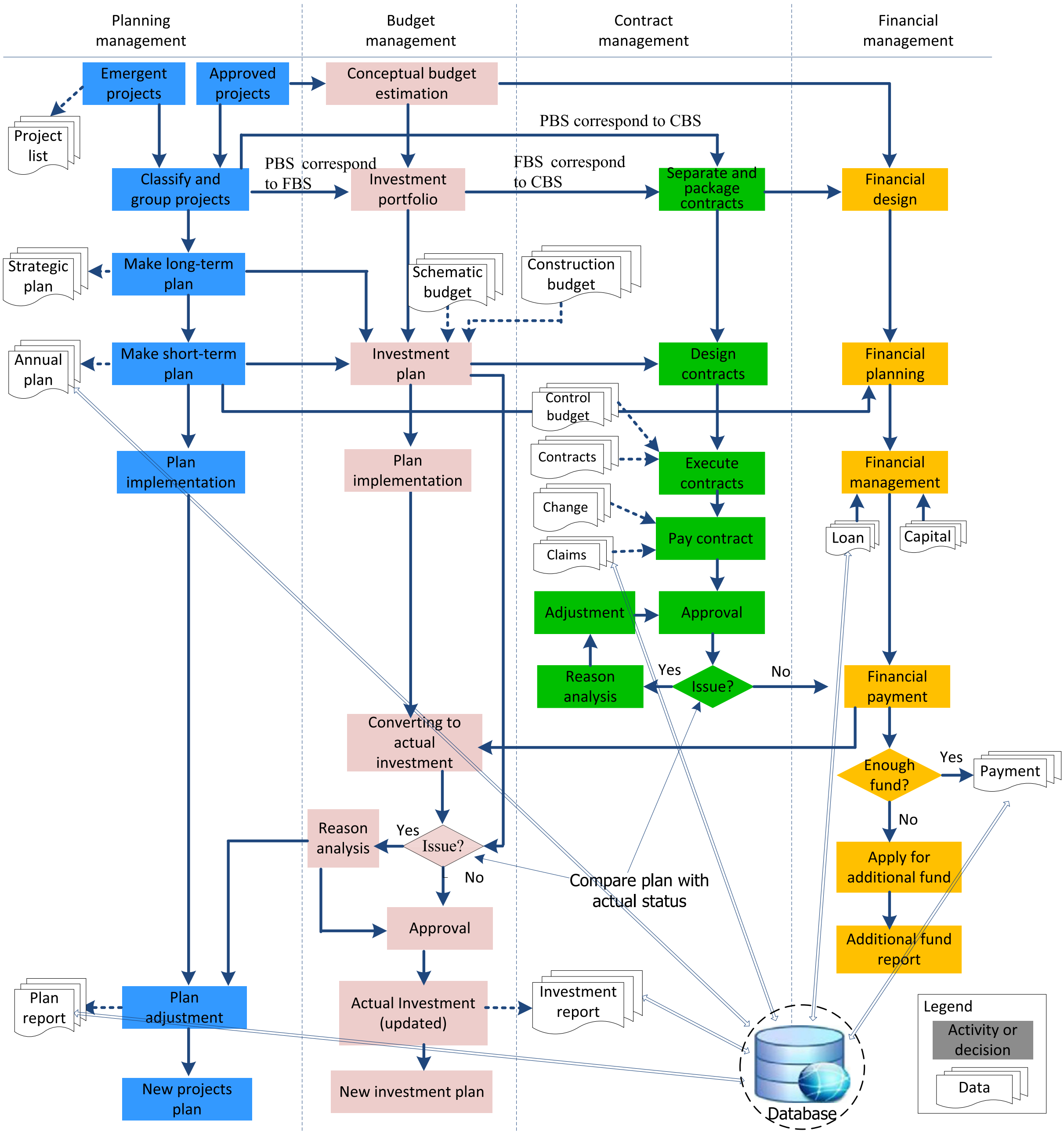

Fig. 5. The integrated processes of project planning, budget, contract and financial management. Note: PBS — Projects Breakdown Structure, FBS — Financial Breakdown Structure, CBS — Construction Breakdown Structure.

variety, decoupling tasks, easing of product upgrade, maintenance, repair, and disposal (Liang and Huang, 2002). Also, senior managers at different hierarchy integrate key information from different modules with limited impacts on the existing system.

The benefits of applying modularized functions and hierarchical structured framework to the CLIPs-MACS development are shown as follows: (1) speed up system development process via parallel development for different modules, (2) minimize the influences of modifying or updating one function on other related functions, (3) increase security of user access, authorities, and data management, (4) meet users' customized requirements by combining and integrating modules, and (5) ease replicating the system to other applicable cities through changing and reorganizing particular modules in order to avoid the overall system redesign.

The system modules are grouped into generic modules and specific modules based on users' requirement. Generic modules are used in all user levels, such as project notification and messages. Specific modules are based on certain levels or functions of users, such as contract management. The specific modules are oriented with different users' categories, demands, and authorities therefore, benefit the most from the modular system architecture due to the ease of software functional integration, development, and maintenance. For example, the business processes of contract management cross-relates with project-wise functional and project departments, as well as external relationships such as administrative safety supervision and public finance and accounting departments. The modular system architecture is shown in Fig. 6.

After assembling all modules together, six primary system function groups can be integrated into the front page of the system. Three approaches discussed above, including systems management, interactive management, and dynamic management, are explained below to meet complex management requirements and to provide customized management and information services.

The 1st function group is the user profile and configuration, which contains roles, positions, organizations, and client logging information. Several functions, such as log-in, correspond to other modular authorities in the 2nd and 3rd function groups.

The 2nd function group is multi-project management, which contains project data center, project front–end management, design management, bidding and tendering management, schedule management, cost management, contract management, and close-out management. The complexity of this function is managed by internal and content focused and system management approach, mentioned in Section 3.2. The availability of functions is controlled by the authorized level of logged users. Project data center is the key interchange database which addresses system-wide information storage and sharing.

The 3rd function group is collaborative work area, which contains news release, process control, information communication, and document management. This part uses interactive management approach to manage the multi-project complexity. The 4th function group is information display and system operations, where the system management and interactive management approach are used for the complexity management.

The 5th function group is information reminding and pushing services, where all relevant news, notifications, reminders, warnings, alerts, processing information are sent automatically based on user's roles and customized requirements. The project complexity is managed by interactive management and dynamic management.

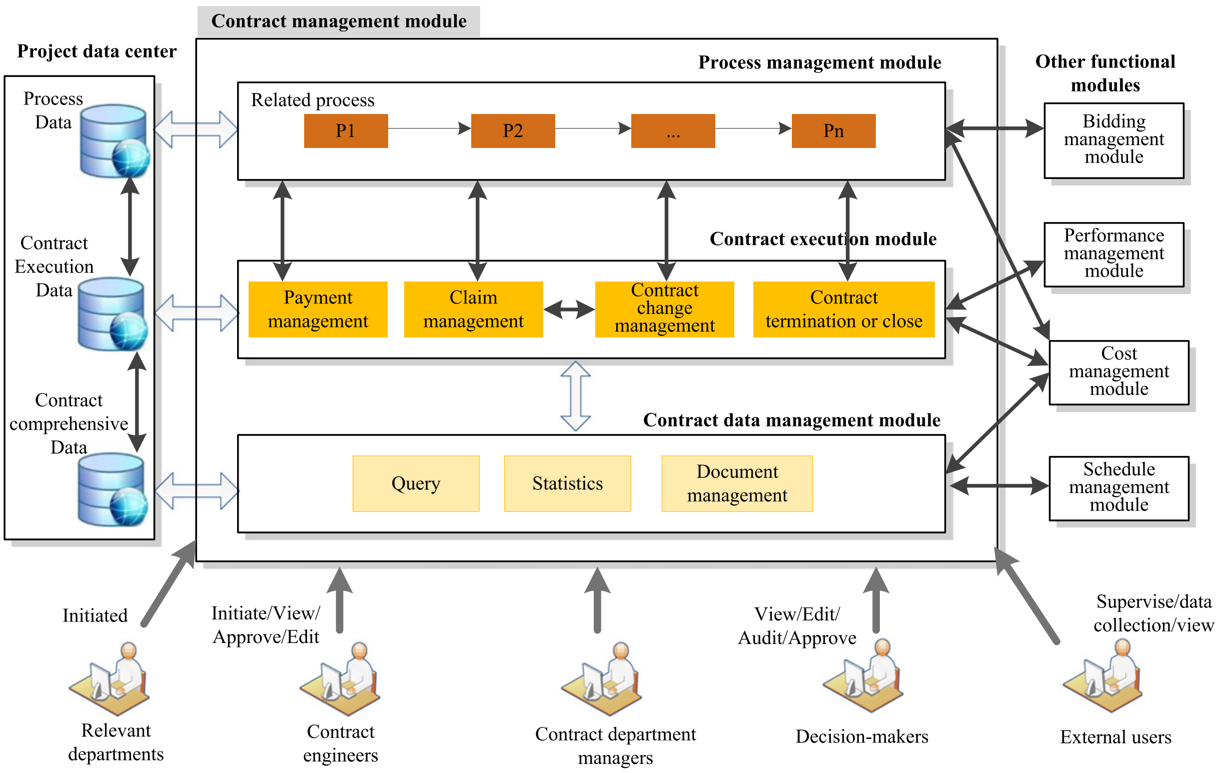

Fig. 6. Modular system architecture for contract management.

The 6th function group is quick operation links, where users can define shortcuts for management functions based on their roles and operating behaviors. Suggested functions include project statistical analysis, department business monitor, issue submission and tracking, project reports, document management, and data input.

6.4. System architecture

PMIS evolves toward a more integrated project lifecycle management by extensive adoption of advanced web-based computing tools (McCullen, 2009). In general, the CLIPs-MACS system is based on J2EE (Java 2 System, Enterprise Edition) architecture. The whole system is divided into two levels: the User Interface (UI) presentation layer and application layer. The application layer consists of business layer, services layer, and data persistent layer. The system architecture is shown in Fig. 7.

The principle of the system architecture is described as "core functional modules, loose modular connections". Every functional module is an independent component in the system, and is developed, deployed, and updated independently. Each component provides its specific service to either external end-users or another system component through a pre-defined and standardized interface. The communication protocol of each component is based on J2EE standard. Such modular design ensures a high reusability for each modular function, making system more efficiency.

The system provides multiple channels to access internet browsers and other remote terminal applications. The system also realizes authorization-based content management. Based on the users' access permission, the system can manage viewable and

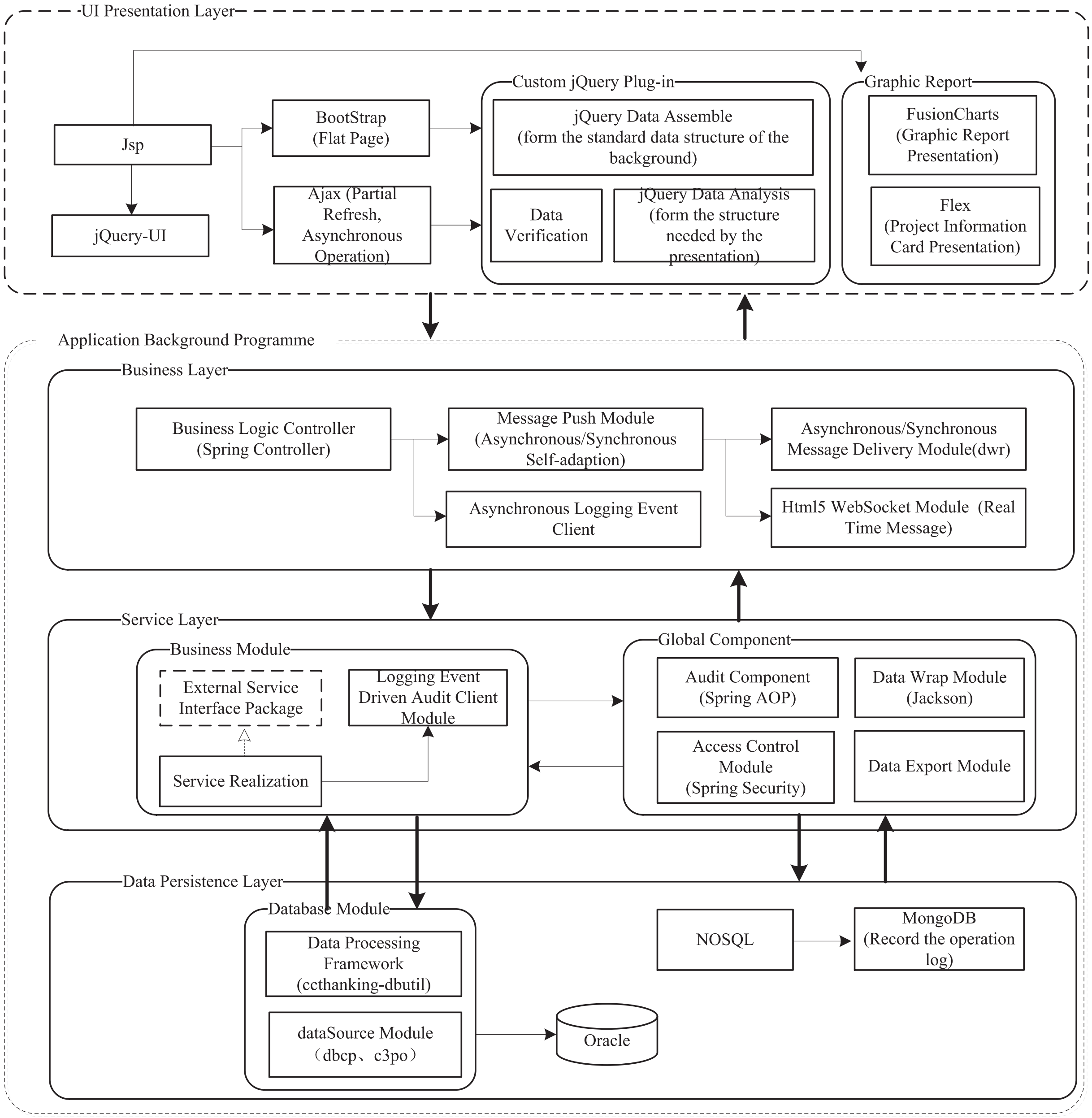

Fig. 7. The system architecture of the CLIPs-MACS.

editable contents, personalized preference management, and access control.

Given the massive amount of information from construction projects, participating parties, and relevant processing tasks, the system chooses user friendly approach and data processing efficiency as key guidelines for the database development and management. For example, the foreground system adopts an integrated technical solution, namely, "*bootstrap* + *jquery* + *json*", for data transmission. Bootstrap, developed by Twitter, is an open source toolkit based on *CSS*/*HTML* framework. *Bootstrap* excels in users' experience and human–computer interaction to ensure the same view and the same user experience across different web applications. The integration of Bootstrap with *jQuery* which is the fastest method to package the *JavaScript* and the use of *Json* as data form, make foreground data processing fast, reduce the data volume, enhance the speed of data transmission, shorten end-users' processing time, and leverage the computing capacity from the client devices. The system display adopts "*div* + *css*" and asynchronous "*JavaScript* + *XML* (*AJAX*)" to allow page partial refresh and to release the server's burden. As to the service support, this system optimizes the data calculation capacity from the background by limiting data queries for only requested data and applying the event-driven query mechanism. In addition, by delaying non-urgent processes to a later time, the background system can release the burden of real-time calculation and improve the system's concurrent service capacity without changing hardware. The database architecture is divided into three levels: database level, data level, and report level. The database level stores and manages all raw data with advanced safety protection and backup plan; the data level uses two dimensional tables to improve the data input and management efficiency; and the report level aims to show personalized and integrated information reporting statements.

7. System pre-deployment evaluations

The value of CLIPs-MACS is to improve the seamless information transmission of multi-project management, the integration and sharing of information, the coordination efficiency among ISDT members, and the timeliness of problem tracking and resolving. System quality and information quality have significant impact on the system use and user satisfaction, and thus result in user's individual impact and eventually cause organization impact (Lee and Yu, 2012). Therefore, prior to official system adoption, verification and validation tests were performed to evaluate the quality of the system. The verification test involved checking the system operating quality that whether all functions meet required specification and work properly. The validation test aims to ensure the system can meet the users' actual demands by testing the data processing, integration and communication capacity, collaborative working environment, and users' feedbacks and satisfaction rating.

In order to perform these tests, a testing team which consists of thirty information technology experts was established. The team members came from a variety of organizations and positions, including representatives from project ISDT and project external stakeholders, such as officials from local government committee of construction finance and accounting department, and project finance specialist from public finance company. The ACM center simulated and recorded all the situations which could be encountered in real project scenarios to test the system capacity involving data, information, events and workflows, decision-making support, and early warning of major issues and risks. Meanwhile, a special task force was established to test the information and communication efficiency of the system. This task force was deliberately formed by identifying five special experts who keep close relations with this system and possessed enough experiences to evaluate the system. The qualification and profile of the five experts are attached in Appendix 2. Table 3 shows the results of system tests and evaluation.

Table 3
System pre-deployment test and evaluation.

Contents	Average score *
System use	
Friendly interface	4.6
Easy to operate	4.4
Friendly integration data display	4.3
Fast system response	4.2
System functions	
Feedback and problem tracking function	4.8
Cove Portfolio management function	4.6
Comprehensive integration function	4.6
Information integration and warning function	4.6
Personalized system function	4.5
Project management function	4.5
Business management function	4.3
Cooperative and coordinative management function	4.3
Program management function	4.2
Dealing with emergencies and unexpectations	4.2
Process interface management function	3.9
System performance	
Offer all needed information	4.9
Information sharing and information transferring	4.8
Monitor and send warnings for project/program/portfolio management	4.7
Timely grasp project, program and portfolio information	4.6
Timely detect, track and solve problems	4.6
Information collection and report	4.6
Help information standardization and transparency for the management	4.5
Effective coordination with relevant members	4.4
Accumulate project knowledge and best practices	4.1

* Note: the scores are sorted in descending order.

The result of system test suggests that 85% of test users reported that the CLIP-MACS created value for the improvement of CLIPs management and complexity management, and confirmed the actual effects, main value, and advantages as follows. (1) Reduce the organizational complexity by centralizing all project lifecycle related information, geographically distributed information, cross-departments coordination information, and enabling real-time information tracking and analysis. The third party audit report (DOHURD, 2011) showed that such efficient organizational communication and collaborations can boost information processing effectiveness and save approximate 5 million Yuan (1 Yuan = 0.16 USD) per annum for the client.

(2) Reduce the financial complexity by visually real-time reporting project financial status to top-level executives in a personalized interface, and providing reliable financial decision-making support from system's integrated financial, contract, budget, and planning functions at both a project and multi-project level. Compare the result of post- and pre-pilot implementation of CLIP-MACS at 2010 and 2009, such integrated financial planning tool decreased 10% of total monetary interests for all borrowed debts (DOHURD, 2011). (3) Reduce the social complexity by improving communication efficiency and data transmission among internal and external of project stakeholders. (4) Reduce the legal complexity by establishing the standard public project management process in highly complex and uncertainty environment, encouraging the transparency of public projects implementation process, and reducing the possibility of administrative power rent-seeking. (5) Reduce the time complexity by analyzing investment and schedule facts at customized scales to increase the controllability of projects status. (6) Reduce the technical complexity by accumulating knowledge management system for complex projects and cultivating experts for public project construction management.

In addition to the task force discussion, the software developers are also interviewed about the technical advantages of the CLIPs-MACS. They testified that the most significant improvement is the time and efforts saved from the re-developing and re-positioning of system functions. The APF design enables the system to adapt to the unavoidable changes quickly, which happened in the project development phase, the commission phase, and turnover stage to other operational agencies. The CLIPs-MACS is more flexible for incurred changes and quicker to be setup up based on its modulated design and connections compared to conventional systems.

However, the pre-deployment verification test also pointed out system limitations and suggestive advices for the future use of CLIPs-MACS, including: (1) project managers recommended expanding current system users to a larger scope to include construction contractors, sub-contractors, and quality supervisors. Their access to the system can leverage the efficiency and promptness of data entry and reduce duplicate data input; (2) functional managers advised that customizing project performance analysis for different managerial perspectives, enabling interactive interfaces for the shared tasks and workflows among functional departments, and endorsing intelligent and automatic multi-project level notification system for milestone event; (3) the ACM center director suggested a standard information exchange interface or protocol between CLIPs-MACS and other administrative agencies; (4) offering automatic data exchange functions to facilitate the data flow of among different sources, for example, the data exchange between personal common software application (i.e. Microsoft Excel) and database server; (5) rich data visualization with integrated with geographic information system and personal remote devices; (6) strengthening the system's risk preparedness of solving unexpected and emergent events with corresponding strategies; and (7) considering system security enhancement and future upgrade depending on the large volume of use in the future.

8. Conclusions

This study uses complexity-based management methods and strategies to develop the web-based project management system, namely CLIPs-MACS, to address the multi-project management efficiency. The system development of CLIPs-MACS is presented based on a real urbanization case in China, City of Changchun. The study first discussed the complexity of CLIPs and their management using complexity and CAS theories, and outlined four corresponding strategies as principles of complexity decomposition. Based on a wide range of survey and interview for end-users, the management requirements were converted into the system functions and information process requirements for the development of CLIPs-MACS. Due to the system changing functions, users, requirements, and political contexts, the study chose the APF development model and modularized functional framework as essential approaches to simplify the complex system development. In addition, web architecture with user-friendly interface and high-efficient data processing package were used to realize the system's requirement. After the system design was completed, a pre-use evaluation test was performed prior to official system deployment to evaluate the quality of the system and to identify potentials for future upgrade.

The pre-use evaluation results realized the expected objectives of managing multi-project complexity. Using the system has positive effect on facilitating management of infrastructure projects, especially multiple infrastructure projects. The CLIPs-MACS advances the practices in terms of streamlining the information communication and coordination across organizations, assisting decision-makers to capture, integrate, and diagnose real time project information to minimize project risks and to increase problem solvency, improving organization controllability for multi-project, and guiding the public project management into a standardized and transparent platform.

This research tried to fill the knowledge gap by applying advanced information system to tackle complex multi-project management and validating its value based on a real case. The development principles and methodology can shed lights on similar infrastructure construction contexts which have concurrent large numbers of interrelated and complex construction projects. BRICS (Brazil, Russia, India, China and South Africa), for instance, have hundreds of cities and regions which are facing such amazing urbanization paces and constructing multi-project every day. This system can be exactly fit to these countries and be further expanded to additional integrated technologies, systems, platforms or devices, such as connecting external project stakeholders and their information systems, enabling mobile devices and geographic information system.

Conflict of interest statement

There is no conflict of interest.

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Appendix 1. Survey questions of multi-projects complexity management requirements from different levels of end-users

User roles	Complexity management requirements (project complexity and project management complexity)
Decision makers	• What is the relationship with government governance mechanism? Which important government departments are involved? What are the interfaces with these departments? (S, O/I) • What's the purpose of CLPP? What are the responsibilities? (F, Ti/–) • What are the most variable factors and uncertain factors? (F, Te, L/E, N) • What is the top risk influencing the project cost, time and quality? (F, Te, L/E, N) • What is the influence from new regulations and policies? How to handle that? (L/A, N) • Who are the most important external stakeholders? Who are needed to become the system users? (S, O/I) • What are the types and scales of the projects in recent years? What is the trend for the future? (Te/A, E) • What are the biggest challenges and problems for the CLPP? What functions should the system provide? (–/E, No) • How to match the organization capabilities and management requirements? What functions should the system provide? (O/A, S) • What is the feedback mechanism? How to make adaptive response? What functions should the system provide? (O/F) • What information and its quality are you expected from the system? (–/E, F, N) • What information should be provided to the government and public society? (F, O/I, F) • What decisions support and warning functions should the system provide? (–/A, F, No)
Department managers, project managers, and multi-projects managers	• What are the types and scales of the projects? (T/E, No) • What are the management responsibilities and business scopes in your departments or projects? (O/I) • What are the most uncertain factors or risk in the project, program and portfolio management? What are the coping strategies? (F, Te, L/E, F, N) • What are the coordinative and relevant external organizations or internal departments? What are the contents? (S, O/I, S) • Whom should you report to? What information is involved in the report? Where does the information come from? (O/I, F) • What information comes from the external environment? What are the features and required quality of the information? (S, O/I, F) • What processes are involved? What is your role in these processes? (O/I, F)
Engineers	• What external organizations do you have the business relations? What kind of relations, such as administrative relations and contractual relations? (S/I, F) • What internal departments do you have the business relations? What are the requirement and quality of the information delivery? (O/I, F) • Where do you work? In-house or on-site? (–/–) • What kind of statistics, forecast and warning information are you expected from the system (–/F, N) • What are uncertain factors influencing the business operation? (–/F, N) • Who are you report to? What information is reported? (O/I) • What are the existing methods to communicate with external stakeholders? What new approaches are you expected for the new system (–/I)

Note: The table is structured into two dimensions: 1) project complexity factors including S — Social complexity, F — Financial complexity, O — Organizational complexity, L — Legal complexity, T — Technical complexity, and Ti — time complexity; and 2) multiple-project management complexity including I — Inter-relationships, A — Adaptability, S — Self-organization, E — Emergence, F — Feedback, and N — Non-linearity.

Appendix 2. Profiles of experts for the pilot test evaluation of the CLIP-MACS implementation

	Expert A	Expert B	Expert C	Expert D	Expert E
Organization	Project management consultants	Client from ACM center	Client from ACM center	Client from ACM center	Government agency
Job title	Project manager	Director for information system	Deputy director for the client organization	Department director	Planning and budget manager
Years working in (complex/large scale) project management experience	15	20	30	20	5
Years working in system development	10	5	3	0	0
Years working at this particular project	3	3	5	5	3
Decision makers: yes/no	No	Yes	Yes	Yes	No

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