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# Coordination and Knowledge Sharing in Construction Project-Based Organization: A Longitudinal Structural Equation Model Analysis

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ABSTRACT

With increasingly advanced construction technology and complex project demand, the construction industry is becoming more and more knowledge-intensive. Effectively coordinating the collective efforts of organization members and sharing knowledge among them are two pivotal and interrelated enablers of organization competitiveness. This study aims to investigate the relationship between individuals' coordination and knowledge sharing behaviors in construction project-based organizations (PBOs). Social network analysis (SNA) with Enron e-mail dataset identified the knowledge sharing network in the Enron Corporation. The e-mail texts were mined to reveal the members' coordination behaviors. Longitudinal structural equation model (SEM) was utilized to analyze the reciprocal relationship between coordination and knowledge sharing. The results suggest that coordination behaviors enable knowledge sharing, while knowledge sharing in turn does not significantly contribute to coordination. Theoretically, it supports the sociology perspective of knowledge sharing in the current empirical analysis. Future studies can replicate the analysis procedure and test the generalizability of the findings in other organization settings. In practice, managers can adopt the proposed approach to identify members' roles in knowledge sharing and coordination, and align their roles with abilities to achieve effective knowledge sharing and coordination.



## 1. Introduction

Faced with increasingly complex demand and fierce market competition, more and more construction companies adopt the project-based organization form to improve project delivery efficiency [5]. Delivering projects as the building blocks of business strategy requires the integration of multidisciplinary expertise [5,20]. Construction PBOs need to tackle the challenges of coordinating and sharing knowledge in interdisciplinary project teams [65]. With the rapid construction technology development, the construction industry is becoming more and more knowledge- and information-intensive. A survey of construction company CEOs suggests that knowledge is deemed as the most critical strategic asset [56]. As a result, knowledge sharing in construction PBOs has become an emerging topic attracting growing research attention [2].

First, knowledge sharing is a core organization capability essential for team integration. From the knowledged-based view (KBV), organizations are networks of members with diverse knowledge backgrounds, and the core capability of organizations is to effectively accumulate, share and utilize the knowledge asssets [22]. This view is especially applicable in construction PBOs, where knowledge sharing acts as the basis of integrating multidisciplinary expertise [33,65]. Second, knowledge sharing enables organization learning and experience transfer [48]. In construction PBOs, sharing lessons learned across projects encourages members to follow best practices and avoid the repetition of mistakes in subsequent projects [49]. It facilitates continuous improvements in project and organizational business performance [20,36]. Third, knowledge sharing acts as an important vehicle for innovation. Various modern communication systems (such as e-mail systems and enterprise management information systems) provide convenient access to unprecedentedly abundant information [17,62]. Knowledge sharing through these communication channels stimulates innovative ideas, incorporates individual innovators into joint efforts and promotes a knowledge spillover effect [62].

Despite the growing awareness of knowledge sharing and the increasing investment on it, organization knowledge sharing practices in the construction industry remain largely poor [31,33,64]. Experience from previous projects cannot be fully utilized in subsequent projects, especially in terms of safety management [61] and contract management [7]. Individual members are the knowledge holders in temporary project teams. They are highly mobile across projects, and may take away precious knowledge often without the awareness to share it. Even with the intention to share, it is difficult for them to determine whether the knowledge is valuable to other projects from the

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standpoint of the individual project [36]. Moreover, different projects may be competing for mutual organization resources, and there is even less incentive to share knowledge with competitors [59].

The above obstacles to knowledge sharing in construction PBOs originate from the various dependencies among projects and project members [59]. As pointed out by Malone and Crowston [42], to coordinate is to manage dependencies. Coordination processes are closely related to the effectiveness of knowledge sharing [51]. The coordination theory conceptualizes coordination as four processes [42], i.e. managing shared resources, managing task dependencies, managing consumer/producer relationships and managing simultaneity constraints. These processes are deeply embodied in classical construction project management techniques such as PERT (Program Evaluation and Review Technique) and line of balance. At the organization level, construction PBO managers coordinate the dependencies among projects to realize the benefits not available by managing them separately [68]. At the project level, project managers coordinate the task dependencies and resource constraints among members [46]. Taken together, the importance of coordination is increasing in the project-based setting where organizations become more reliant on interdisciplinary teams of specialists [19].

Members' coordination performance affects their ability to approach others, obtain information, refine knowledge and become active in knowledge sharing [33]. Active members in the knowledge sharing network, in turn, are able to process timely information and valuable knowledge, which is the basis of effective coordination [17]. Many previous studies examined the relationship between knowledge sharing and coordination [12,29,50], whereas the empirical findings are mixed in terms of causality. This limitation induces the confusion on whether organization managers can improve knowledge sharing by enhancing coordination, or they can improve coordination by motivating knowledge sharing.

This study aims to bridge this research gap by empirical analysis on real-world data from the Enron Corporation, which is a giant engineering company specialized in power and electricity. Social Network Analysis (SNA), text mining technique and Latent Variable Cross-Lagged Panel model (LCLP, a kind of longitudinal SEM) are incorporated to extract data and analyze the causal relationship between knowledge sharing and coordination. The theoretical implication of the findings is that coordination acts as the antecedent of knowledge sharing, while knowledge sharing in turn does not significantly contribute to coordination. Practically, organization managers can improve members' coordination behaviors as an important enabler for knowledge sharing.

Subsequent sections focus on the relationship between knowledge sharing and coordination, and are organized as follows. Section 2 reviews literature on knowledge sharing and coordination in PBOs, and identifies implications and limitations in previous studies. Section 3 elaborates on the empirical analysis procedure and methods, including SNA, text mining and LCLP. Section 4 summarizes the empirical results, and based on these, discussion and conclusions are presented in Sections 5 and 6 respectively.

## 2. Literature review

### 2.1. Knowledge sharing in PBOs

Knowledge management in PBOs involves knowledge obtaining, sharing, storing, applying, integration and renovation processes, in which knowledge sharing is a critical process [48]. Without adequate knowledge sharing, knowledge leakage will lead to repeated mistakes, duplicated work, lack of innovation and ultimately organization inefficiency. This is supported by Zhang and El-Diraby [63], who underlined the importance of knowledge sharing in complex project enviroment. Reich, et al. [48] further pointed out that growth in knowledge stock does not necessarily contribute to competitive advantage, and knowledge sharing acts as the essential mediator.

#### 2.1.1. A social network perspective of knowledge sharing

In order to motivate knowledge sharing, many researchers identified critical enablers such as team cohesion [3] and organization culture [3,20]; constructed information systems to build a collaborative knowledge sharing environment [51]. Despite the abundant research efforts, numerous organizations are struggling with problems in knowledge sharing [31,36]. It has been widely reported that the benefits obtained from knowledge sharing do not match the investment on it, and approximately half of the knowledge management systems failed their original goals [25,33]. The reasons are twofold. First, the traditional realistic view of knowledge emphasizes on the knowledge storage and communication technology, while pays little attention to the social and behavioral aspects [14]. So there is a lack of efforts to accommodate the knowledge management systems to organization contexts. Second, most existing studies were conducted at the organization level, without elaborative investigation on individual members, who are the actual knowledge holders [33].

Knowledge sharing is an interactive process between organization members [37]. Knowledge sharing relationships constitute a social network joining all members together, and no knowledge sharing activity is possible outside the network [51,56,66,69]. In the same vein, construction PBOs are not merely collections of contractual arrangements, but complex networks of members as knowledge holders [22]. Knowledge sharing is inherently a network process, and thus, should be understood from the network perspective [14]. Anklam [2] pointed out that knowledge flows along communication paths in organization network, so SNA can be performed to obtain deeper insights on knowledge sharing in business activities. Zhang and Wang [66] and Le, et al. [41] studied safety and health knowledge sharing in construction organizations by network analysis. In this light, we adopt the network perspective and model knowledge sharing by social network analysis.

#### 2.1.2. An information hierarchy perspective of knowledge sharing

Knowledge sharing is intangible in nature [69]. Underlying the definition of knowledge is the implicit intuition that data, information, knowledge and wisdom constitute a pyramid structure, often quoted as the information hierarchy [70,71].

To clarify the information hierarchy in construction project settings, we take the concrete temperature control process as an illustrative example. For the purpose of crack prevention, the temperature of newly poured concrete is gauged. These temperature *data*, observed either manually or automatically, describe the properties of objects, events and their environments [71]. They can be formatted, reduced and thereafter documented as *information* in project implementation reports. The data processing procedures produce *information* and derive concise answers to questions such as "what was the average temperature within 3 days" and "how many cracks developed due to high temperature" [70]. By identifying common patterns in the *information*, *knowledge* (such as "how does high temperature influence concrete cracking" and "what is the permissible temperature to prevent cracks") can be obtained. The transformation of *information* to *knowledge* produces actionable principles such as "when should we take measures to control the temperature of concrete". Combining these principles facilitates more informed decisions and creates the ultimate organizational *wisdom* [70]. With a comprehensive description on organization knowledge structure, information hierarchy provides several useful implications to modelling knowledge sharing.

First, the boundaries between hierarchies are vague, especially the boundary between *information* and *knowledge*. Knowledge sharing is embodied in information sharing, and it is arbitrary to make a definitive distinction between the two constructs [70]. This is reflected in the difficulty of capturing knowledge sharing by questionnaire survey, since it is no easy task for respondents to tell knowledge sharing from information sharing and data sharing [25]. Zhao and Chen [67] suggested to extract knowledge sharing networks from enterprise information systems, instead of trying to distinguish knowledge from information. Discovering knowledge sharing processes from information sharing is an informative approach widely adopted in previous studies [57,65].

Second, as the raw *data* climb up the hierarchies of *information*, *knowledge* and *wisdom*, they become less contextualized, and increasingly abstract to be shared among organization members. For example, it is easy to share project implementation reports by e-mails, but much more efforts are needed to make the underlying experience and knowledge completely shared [72]. Knowledge sharing is inherently an interactive process [50,57,69]. It involves codifying knowledge in the form of information by the knowledge holders, transferring the information by communication media, and obtaining mutual understanding by the recipients [14]. The reciprocal information communications on a common topic is pivotal to knowledge sharing, and can be used to identify the intangible knowledge sharing process [69,73].

Since it is costly (if not impossible) to conduct an experiment in a real-world organization and directly observe memebers' behaviors [74], there is a lack of a perfectly objective measurement of knowledge sharing. From the information hierarchy perspective, the reciprocal information sharing on a common topic is a strong indication and good approximation to knowledge sharing [75]. Based on a survey in construction companies, Sik-wah Fong and Chu [56] identified chatting, meetings, phone calls and e-mails as the most important knowledge sharing channels. Among them, e-mail is a very informative media, which not only conveys the information within the e-mail texts, but also implies knowledge sharing behaviors beyond them [40,76]. For example, members may exchange e-mails to arrange a meeting, which provides an opportunity for knowledge sharing. This is further supported by Grippa [25] who found that e-mail communications capture more than 90% of knowledge sharing relationships. This phenomenon is especially obvious in the large construction PBOs with geographically dispersed projects and members [25,72]. In this light, many researchers mined e-mail data to discover knowledge-intensive processes [57], evaluate knowledge sharing status [37], and study the determinants of effective knowledge sharing [12,27,29,32].

Based on the social network and information hierarchy perspectives of knowledge sharing, we extracted the e-mail network and identified knowledge sharing behaviors from reciprocal e-mails on a common topic.

### 2.2. Coordination theory and its implications for PBOs

Coordination structure has been evolving with organization structure [50]. In functional organizations, traditional coordination builds on mechanisms, which involves planning routinized works and communicating among well-defined management hierarchies [19]. These coordination mechanisms are considered optimal in organizations with stable and predictable operations [50]. However, the growing technological complexity results in organizational complexity in the construction industry [33]. Frequent needs for collaboration among cross-functional experts reshape the organization structure into a project-based form. Within the project-based setting, traditional coordination mechanisms fail to accommodate to dynamic business environment, bespoken project demand and flat organization structure [19]. Malone and Crowston [42] identified the need for an interdisplinary coordination theory, and integrated insights from organization theory, economics and computer science in theory development. The proposed coordination theory has been widely adopted in construction management research [12,13,27,29]. It conceptualizes coordination as managing dependencies through four processes:

1. Managing shared resources. Whenever multiple activities share some mutual resources, the priority of activities should be determined and coordinated. Prioritizing projects in a portfolio and allocating resources are the primary processes to manage shared resources in portfolio management. Knowledge is also an important organization resource to be carefully accumulated and shared by collective efforts.
2. Managing producer/consumer relationships. The deliverables produced by some activities are consumed by other activities as inputs. This kind of relationships is common among projects in the same program which aims to obtain strategic benefits not available by managing them separately.
3. Managing simultaneity constraints. Some activities need to occur at the same time or cannot occur at the same time. For example, when arranging a meeting to share knowledge across projects, at least one expert from each project needs to be present.
4. Managing task/subtask dependencies. Tasks are decomposed into subtasks in the work breakdown structure (WBS), and the fulfillment of tasks depends on the fulfillment of subtasks. Coordinating the task/subtask relationship is essential to align knowledge and expertise with task/subtask requirements [33].

Similar to knowledge sharing, coordination behaviors are intangible and difficult to quantify [42]. Many researchers conducted questionnaire surveys [52], expert interviews [19] and grounded qualitative analyses [17] to study organization coordination, but found it difficult to eliminate subjective bias [16]. Hossain and Wu [29] proposed a *process-action* text mining method to quantify coordination behaviors based on key phrases reflecting the coordination processes prescribed by the coordination theory. Many subsequent studies build on this method to quantify members' coordination roles [12,27] and identify collaborative processes in organizations [57]. We adopted this approach to quantify members' coordination behaviors in the Enron Corporation.

### 2.3. The causal relationship between coordination and knowledge sharing

Coordination and knowledge sharing in PBOs are highly correlated social behaviors. However, empirical evidence on their causal relationship is mixed, and there exist two competing theoretical perspectives, i.e. cognition perspective and sociology perspective [14].

Cognition perspective considers knowledge sharing as the basis of effective coordination [15,38]. Organization knowledge can be classified into long-term knowledge and fleeting knowledge, according to its contribution to the fulfillment of tasks [17]. The long-term knowledge is obtained during a long period of education and training, and contributes directly to members' task ability. Common long-term knowledge is necessary for members to make sense in discussions, and acts as the basis of coordination. Fleeting knowledge, on the other hand, is situational knowledge specific to the current team, e.g. which member can provide help for a specific problem. Fleeting knowledge conduces to team awareness and hence team coordination [17]. In construction project-based organization settings, where working constellations change frequently, fleeting knowledge is especially important for coordination. Informed by these arguments, we propose hypothesis 1.

**Hypothesis 1.** *Members' knowledge sharing behaviors conduce to their coordination behaviors.*

From the sociology perspective, coordination is the antecedent of knowledge sharing [14]. Organization knowledge resides in individual members, and knowledge sharing is a social behavior in the organization network. The more a member acts as a coordinator, the more useful information he/she can approach, and hence the more active he/she tends to be in the knowledge sharing network [51,59]. In this light, we propose hypothesis 2.

**Hypothesis 2.** *Member's coordination behaviors conduce to their knowledge sharing behaviors.*

The studies by Enemark, et al. [15] and Espinosa and Clark [16] support the cognition perspective with theoretical analysis and empirical results. Tsai [59], on the other hand, provided empirical support to the sociology perspective with SNA on a multi-unit organization. However, the effect of knowledge sharing on coordination was not examined. Several studies on similar topics also imply support for the sociology perspective, for example, Santoro [51] constructed a coordination system in an organization network to foster knowledge sharing. In addition, some other studies alluded to the co-existence of both perspectives [26].

Taken together, based on the existing empirical evidence, it cannot be concluded which perspective dominates, or whether there is a reciprocal causal relationship between the two constructs. This limitation is attributed to the lack of a longitudinal study, which enables causal judgment [29]. Moreover, as elaborated above, construction PBOs face unique challenges with coordination and knowledge sharing, while there is a lack of study conducted in this organization setting. To bridge this gap, this study builds on the longitudinal data in the Enron Dataset, and reveals the causal relationship between coordination and knowledge sharing by longitudinal SEM.

### 2.4. Existing research on the Enron dataset

The Enron Corporation was a giant construction PBO with major business in power and electricity engineering. In 2000, it was the seventh largest business organization in the U.S. by revenue, and was rated as "America's Most Innovative Company" by *Fortune* magazine [77]. News about the ambitious corporation and its international projects (such as the Dabhol project in India) was frequently reported by Engineering News Record (ENR) as headlines [78]. However, at the end of 2001, it went bankrupt due to an accounting fraud scandal. The Federal Energy Regulatory Commission (FERC) led an inquiry into the scandal, and, in May 2002, publicly released the e-mails between 158 employees which are the prototype of the Enron dataset. Researchers from MIT purchased the e-mail dataset, and corrected integrity problems. This resulted in a corpus containing 517431 e-mails among 150 members. Shetty and Adibi [54] cleared duplicate e-mails and visulized the e-mail communication network. Diesner, et al. [11] further identified 557 e-mail senders, and matched them with organization members.

The Enron dataset contains authentic records on the e-mail communications among members in a real-world construction PBO during 1998-2002. It provides precious data for studies on information science [39], linguistics [47] and construction management [27–29]. As suggested by Diesner, et al. [10], different analysis approaches should be developed in different studies on the Enron dataset according to their research objectives. This study, based on the original and most widely-used version of the Enron dataset (containing 517431 e-mails), extracts a knowledge sharing network and mines e-mail texts to identify members' coordination behaviors.

## 3. Research methods

### 3.1. Knowledge sharing network analysis

As above, extracting knowledge sharing network from e-mail communication has the advantage of being simple, objective and informative [25,37,57]. Many previous studies developed e-mail network extraction methods [10,11,13,27–29,40,44], however, given the purpose of identifying knowledge sharing network, we made several modifications.

1. Extract data on a quarterly basis. E-mail is a timely communication medium, and e-mails sent at different times reflect the members' knowledge sharing behavior in different periods. According to the previous findings [1,40], e-mail networks remain stable on a quarterly basis. Besides, the organization social network may manifest complex dynamics during crisis [28]. Based on these considerations, e-mail data in three pre-crisis quarters (Q3 and Q4 in 2000 and Q1 in 2001), including 165624 e-mails, is extracted for further analysis.
2. Filter out those e-mails sent to or received from outside the Enron Corporation. PBOs integrate external resources in projects, and the dataset includes many e-mails with project participants outside the organization [11]. The existence of organization boundary tends to distort knowledge sharing behaviors [45]. Therefore, only the 78291 e-mails among the 150 Enron employees were analyzed.
3. Select e-mails in e-mail threads. Knowledge sharing is bidirectional and a reciprocal interaction to express, examine and diffuse knowledge [14,57]. As elaborated above, we identify knowledge sharing by a series of e-mails exchanged consecutively (continuous in time) on the same topic, defined as e-mail threads [35,39]. In order to check if an e-mail belongs to an e-mail thread, we need to determine the minimum numbers of e-mails in a thread. Some researchers suggested that all interactive e-mails be included to capture all potential knowledge sharing behaviors [27,79], i.e. an e-mail thread exists between two individuals if at least one e-mail was sent to and received from each other [35]. This approach inevitably risks including e-mails not conveying knowledge [40]. Some reseachers suggested to improve the preciseness by setting a higher threshold level, for example, Adamic and Adar [1] identified knowledge sharing by the e-mail threads containing at least 6 e-mails sent both ways. However, a higher threshold is also debatable, since it may miss some knowledge sharing behaviors through fewer e-mail exchanges [25]. In fact, there is a trade-off between comprehensiveness and preciseness when setting the threshold. Based on the specific dataset used in this study and previous studies on it [27,29], we chose a conservative threshold level of four, and dropped e-mails between members who exchanged less than four e-mails. E-mails from public e-mail addresses and e-mails with CC and BCC recipient types were also dropped to eliminate passive information diffusion [1,11]. In this way, 15679 e-mails from 147 members were selected (3 members were found to have no e-mail thread communication with others).

Based on the above steps, we derived the knowledge sharing network in the Enron Corporation by defining e-mail thread as the tie from the sender to the recipient. The number of exchanged e-mails is defined as the weight of the tie. Organization members' positions in knowledge sharing network indicate how active they are in knowledge sharing. Practically, we calculate centrality indices to quantify the members' knowledge sharing roles.

1. **Betweenness centrality** is defined as the member's total frequency of locating on the shortest paths between other members [23]. It measures a member's role as an intermediary in the network. Members with high betweenness centrality are also named "knowledge broker". Betweenness centrality indicates the ability to control knowledge sharing paths.
2. **Closeness centrality** is calculated as the reciprocal of the member's average shortest distances from other members [4]. It is a measurement of the member's ability to approach others in a short time. Directed network differentiates between e-mails sent and received, and in-closeness centrality and out-closeness centrality can be calculated respectively. In knowledge management literature, it has been widely accepted that out-closeness centrality makes much more sense in knowledge sharing [29]. Thus, we only included out-closeness centrality as an indicator of knowledge sharing.
3. **Degree centrality** refers to the number of connections a member has with others. Similar to closeness centrality, in-degree centrality and out-degree centrality can be calculated in directed networks. Degree centrality mirrors the activeness of members in knowledge sharing networks.

Betweenness centrality, out-closeness centrality, in-degree centrality and out-degree centrality reflect different aspects of members' roles in knowledge sharing activities. They were adopted as the indicators of knowledge sharing in this study.

### 3.2. Quantifying coordination by e-mail text mining

According to the coordination theory, coordination processes include managing shared resources (MSR), managing producer/consumer relationships (MCR), managing simultaneity constraints (MSC) and managing task/subtask dependencies (MTD). Since coordinative actions are historically situated and culturally embedded, there exists no universal language of coordination in different contexts [29]. Hossain and Wu [29], based on the four coordination processes, quantified coordination behaviors by an e-mail text mining approach which has been widely adopted in subsequent studies [12,13,27,28]. We followed this approach, whereas our research target is the whole organization rather than individual projects as in Hossain and Wu [29]. So the original approaches to select training dataset and test the validity of key phrases were modified, as shown in Fig. 1.

First, we randomly selected 200 e-mails as the training dataset each time, annotated key phrases indicating coordination, and categorized the phrases into the four processes of coordination [34]. This procedure was performed iteratively, and after 7 iterations (1400 e-mails annotated), the construct of coordination became saturated, i.e. the collection of key phrases did not further augment. However, there may be e-mails embodying coordination without using the key phrases or e-mails containing some of the key phrases without actually embodying coordination (see Appendix A for detailed examples). In order to test the validity of the extracted key phrases, we randomly selected another 1400 e-mails as the testing dataset.

Second, we annotated each e-mail in the training and testing datasets in terms of whether it reflects the sender's coordination behavior in the four processes. For example, if e-mail No.1 in the training dataset indicates the management of shared resources and no other kind of coordination activity, then the variable MSR was coded 1 and the others were coded 0. We also calculated dummy variables for each key phrase indicating whether the key phrase was contained in the e-mails. In this way, we transformed the datasets into a numerical form ready for further analysis.

Third, we trained support vector machine (SVM) models for each coordination process to predict whether the process is embodied in e-mails, based on the variables of key phrases. The training dataset was fed into the SVM models to select the best models, and then the best models were tested on the testing dataset. To evaluate the performance of the models, we adopted the frequently used confusion table and evaluation measures [34]. Table 1 is a typical confusion table comparing the results of SVM prediction with manul annotation. TC denotes the number of e-mails that truly embody coordination behavior (identified by manual annotation) and are also predicted to embody coordination by SVM. Similarly, TN denotes the number of e-mails that truly do not and are also not predicted to embody coordination; FC denotes the number of e-mails that truly do not but are predicted to embody coordination; FN denotes the number of e-mails that truly do but are not predicted to embody coordination.

$$\text{Accuracy} = \frac{TC + TN}{TC + FC + FN + TN} \tag{1}$$

$$F\text{-measure} = \frac{2 \times \text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \tag{2}$$

$$\text{Precision} = \frac{TC}{TC + FC} \tag{3}$$

$$\text{Recall} = \frac{TC}{TC + FN} \tag{4}$$

Based on TC, TN, FC and FN, the evaluation measures can be calculated by Eqs. (1) to (4), and the results are presented in Table 2. For the purpose of comparison, we also trained SVM models based on the key phrases proposed by Hossain and Wu [29]. Both of the results are

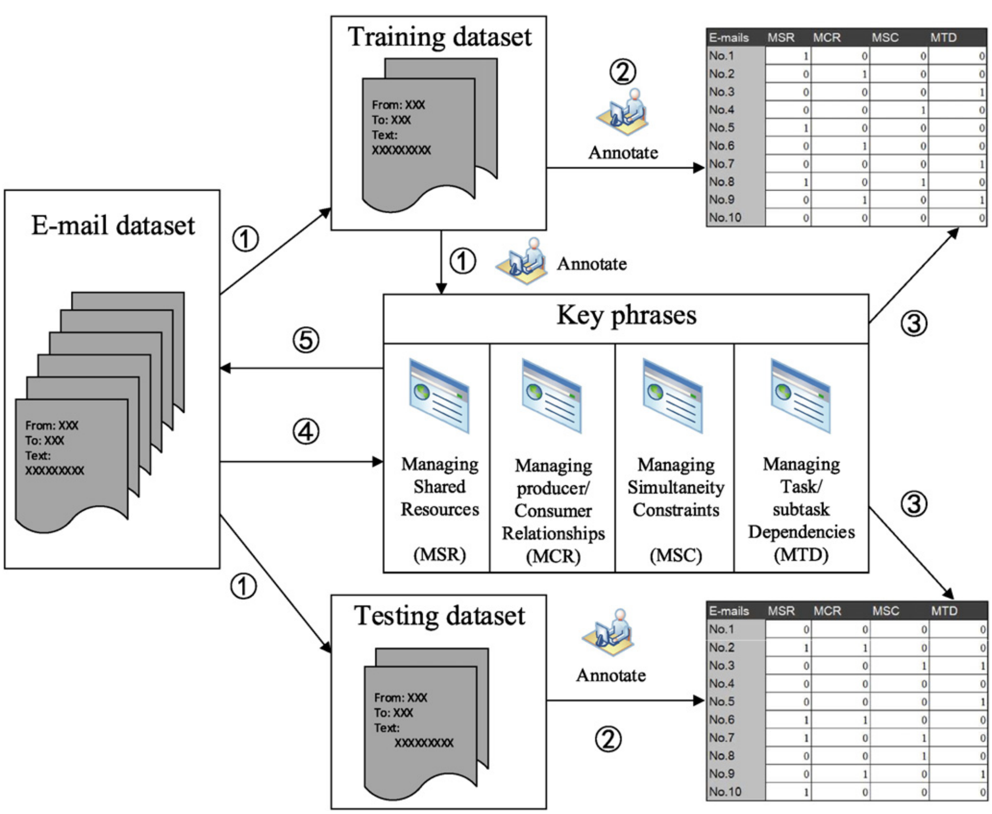


**Fig. 1.** E-mail text mining procedure

**Table 1**
A typical confusion table

| Prediction by SVM | Annotation | |
|---|---|---|
| | C | nC |
| C | True Coordination (TC) | False Coordination (FC) |
| nC | False Non-coordination (FN) | True Non-coordination (TN) |

**Note:** C denotes the emergence of the coordination process, and nC denotes the contrary.

satisfactory, and since our key phrases were extracted from the dataset used in this study, they performed slightly better. These results indicate that the annotated key phrases have sufficient predictive power to identify coordination processes.

Fourth, the key phrases were weighted as the base two log of the total usage frequency of the words to avoid the non-normality problem, as suggested by Hossain and Wu [29] and Dogan et al. [13]. The datasets used in this study and Hossain and Wu [29] are obtained from the same organization, and hence the two sets of key phrases should be comparable. Deviations between the weight of the same phrases were calculated, and the largest relative deviation appears in phrase "*Look into*" (34.2%, from 7.46 in Hossain and Wu [29] to 4.91 in this study). The Pearson correlation between the two groups of weights is 0.781, indicating strong consistency. This further validates the construct of coordination in this organization context.

Fifth, the scores of the four coordination processes in each e-mail were calculated and assigned to the e-mail sender, based on the weight of key phrases (see Appendix A example 1 for a detailed example). The total coordination scores were calculated for each member by summing up the scores of the e-mails they sent. The scores of four coordination processes were calculated separately to capture different aspects of coordination, and all the four aspects were used as the indicators of coordination.

### 3.3. Latent Variable Cross-Lagged Panel model

Structural Equation Modelling (SEM) is a multivariate statistical method to study the relationships among latent variables. Given its advantage of modelling the relationships among latent constructs with multiple indicators, it has been widely adopted in many previous studies on management, education and economics [61]. Xiong, et al. [61] comprehensively reviewed the use of SEM in construction management studies, and found that almost all previous studies were built on cross-sectional data. He underlined the importance of adopting longitudinal SEM to reveal the causal relationships among variables. Latent Variable Cross-Lagged Panel (LCLP) model is a kind of longitudinal SEM based on continuous observations on the same sample (known as panel data). In view of its ability to model reciprocal causal relationships, we constructed a LCLP model (as shown in Fig. 2) to study the causal relationship between coordination and knowledge sharing.

Knowledge sharing and coordination in different periods are modelled as distinct latent variables. The parameter $\gamma_0$ denotes the

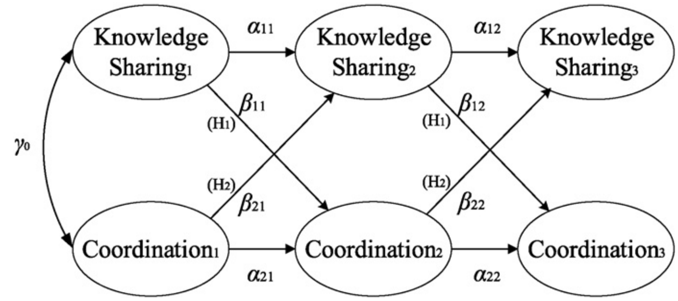


**Fig. 2.** LCLP model of the relationship between knowledge sharing and coordination

free correlation between knowledge sharing and coordination in the first period, estimated automatically in the LCLP model. The auto-regression coefficients ($\alpha$) indicate the correlation between the same latent variable in consecutive periods. The cross-lagged coefficients $\beta_{11}$, $\beta_{12}$ measure the effects of previous knowledge sharing activities on subsequent coordination activities, and $\beta_{21}$, $\beta_{22}$ measure the contrary. Based on the axiom that the cause precedes the effect, $\beta_{11}$, $\beta_{12}$ corresponds to H1, and $\beta_{21}$, $\beta_{22}$ corresponds to H2.

According to the basic assumptions of LCLP, the model parameters should satisfy several conditions. First, the measurement invariance condition suggests that the indicator loadings of the same construct should be invariant across multiple periods, since they measure the same construct. Second, the cross-lagged relationships should be the same across periods, since they measure the same effect. Therefore, the three-wave model is typically developed to test the invariance of cross-lagged relationships ($\beta_{11} = \beta_{12}$ and $\beta_{21} = \beta_{22}$). In order to test the LCLP model and the two model constraints, we followed six steps in our empirical analysis, as illustrated in Fig. 3.

1. Use SNA method in 3.1 to calculate knowledge sharing indicators, and use text mining method in 3.2 to calculate coordination indicators.
2. Fit the baseline model, and obtain the model result (R1). The baseline model contains only the auto-regression relationships, and assumes no cross-lagged relationship. The measurement invariance constraint is maintained to enable comparison with the target model.
3. Fit the unconstrained model, and obtain the model result (R2). In this model, both auto-regression and cross-lagged relationships are analyzed, but the two constraints are relaxed to examine the tenability of the constraints by comparison with the target model.
4. Fit the target model, and obtain the model result (R3). The target model contains all the relationships and model constraints. With more relationships considered, the target model should achieve better model fit than the baseline model. If R3 is significantly better than R1, we should accept the target model. With fewer constraints in place, R2 should achieve better model fit compared to the target

**Table 2**
Confusion tables and evaluation measures

| Processes | | Annotation | | Accuracy | | Precision | | Recall | | F-measure | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | SVM | C | nC | T | H | T | H | T | H | T | H |
| Managing shared resources | C | 347 | 63 | 0.885 | 0.720 | 0.846 | 0.669 | 0.780 | 0.675 | 0.847 | 0.672 |
| | nC | 93 | 897 | | | | | | | | |
| Managing task/subtask dependencies | C | 380 | 74 | 0.881 | 0.884 | 0.837 | 0.828 | 0.803 | 0.783 | 0.820 | 0.805 |
| | nC | 93 | 853 | | | | | | | | |
| Managing producer/consumer relationships | C | 441 | 131 | 0.816 | 0.552 | 0.771 | 0.583 | 0.776 | 0.566 | 0.773 | 0.574 |
| | nC | 127 | 701 | | | | | | | | |
| Managing simultaneity constraints | C | 259 | 95 | 0.857 | 0.664 | 0.732 | 0.444 | 0.712 | 0.642 | 0.722 | 0.524 |
| | nC | 105 | 941 | | | | | | | | |

**Note:** T denotes the results based on the key phrases in this study; H denotes the results based on Hossain and Wu's key phrases.

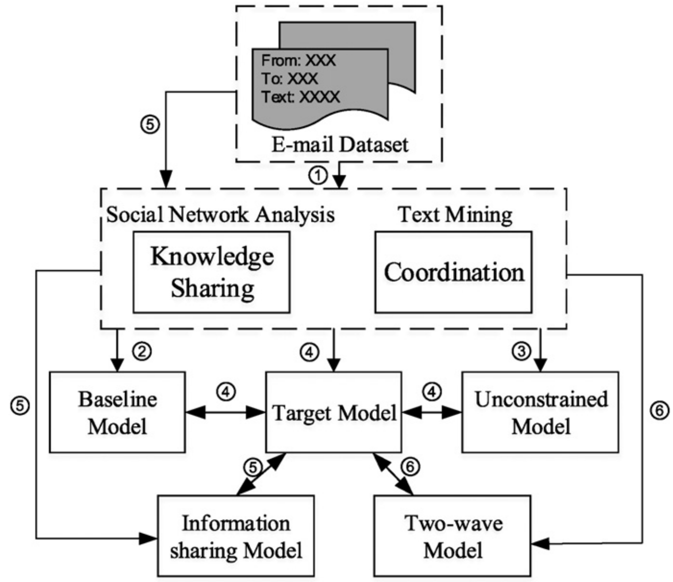


**Fig. 3.** Procedure to test the LCLP model

model. However, if the improvement is not significant, we should consider the constraints tenable.

5. Test the robustness of the construct. Extract information sharing data from the whole e-mail dataset (including all the 78291 e-mails). Fit the LCLP model with information sharing data (R5) to test whether the reciprocal relationships also exist between information sharing and coordination, or they merely hold for knowledge sharing.
6. Test the robustness of the causal relationship. The cross-lagged effects should be examined over multiple time courses to check whether the causal pattern varies with different time lags. Following the commonly used robustness test method [53], we constructed a two-wave model (R4) based on the data in period 1 and 3.

## 4. Empirical results

### 4.1. Results of LCLP

We extracted knowledge sharing network data from the refined dataset and visualized it with *UCINET* software. Fig. 4 shows the knowledge sharing network in the first period (Q3 2000). Members with higher positions are denoted with larger numbers and nodes with darker color, and there are totally 8 hierarchies of positions as shown in Fig. 4. The size of each node is proportional to the member's total coordination score (the sum of scores in the four coordination processes). As shown in Fig. 4, coordinative members (nodes with large size) tend to hold central positions in the knowledge sharing network, while members with higher formal positions are distributed across the whole network. This coincides with the Hossain's findings that network position is more closely related to coordination rather than formal organization positions [27].

Based on the indicators calculated from SNA and text mining, Cronbach's $\alpha$ of each latent variable was calculated with the help of *SPSS* (Statistical Product and Service Solutions). As shown in Table 4, all the 6 latent variables are reliable for further SEM analysis with Cronbach's $\alpha$ above the threshold level of 0.7 [21].

We fitted the models in step 2 to step 4 by MLMV (Mean- and Variance- Adjusted Maximum Likelihood) method with the help of *Mplus* software to overcome the non-normality problem. According to the model fit indices listed in Table 5, the data fit satisfactorily with all the 3 models ($CFI>0.85$, $TLI>0.85$, $RMSEA<0.08$, $SRMR<0.08$, $\chi^2/df<2$) [43]. Compared to the target model, the degree of freedom of the baseline model decreased by 2 with two more cross-lagged coefficients ($\beta_1$ and $\beta_2$) to be estimated. The comparison between R1 and R3 suggests significant improvement in model fit ($\Delta\chi^2(2)=12.862$, $p<0.05$), so we consider the cross-lagged effects significant. Compared to the target model, measurement invariance and effect invariance constraints were relaxed, nevertheless, the comparison between R2 and R3 indicates no significant model fit improvement ($\Delta\chi^2(14)=22.730$, $p>0.05$). Therefore, the model constraints were supported, and the target model is the most parsimonious and accurate in modeling the cross-lagged relationship between knowledge sharing and coordination. The path coefficients of the target model are illustrated in Fig. 5.

Since there are measurement invariance constraints in the target model, the factor loadings are consistent during three periods, and only the factor loadings in the first period are denoted. As shown in Fig. 5, all indicators have high factor loadings, except for *out-closeness centrality*, whose loading (0.486) is slightly lower than the threshold level of 0.5 [43]. This suggests that the latent variables have satisfactory convergent validity. According to path coefficients in Fig. 5, hypothesis 2 is supported in the current empirical analysis since coordination behaviors in previous periods contribute significantly to knowledge

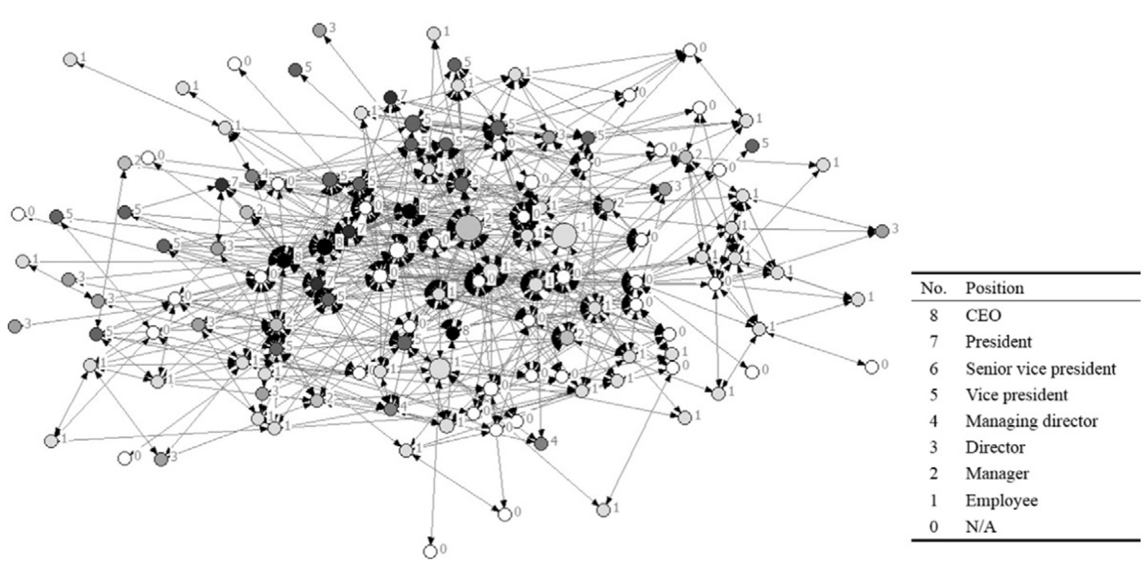


**Fig. 4.** Knowledge sharing network in the first period (Q3 2000)

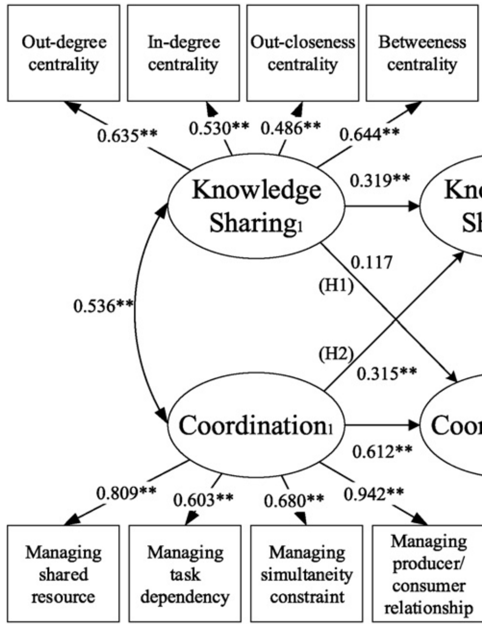


**Fig. 5.** The results of the target model Note: ** denotes the significance level of the path coefficient $p<0.01$

sharing in subsequent periods. However, the reverse does not hold, suggesting that hypothesis 1 is not supported in the current empirical study.

*4.2. Robustness test*

The two-wave model was fitted to check the robustness of the target three-wave model. Knowledge sharing and coordination in the first period act as the predictors of the two constructs in the third period. The model results (R4) suggest satisfactory model fit, as listed in Table 6. Model coefficients in the two-wave and three-wave models are largely consistent, while hypothesis 1 is also weakly supported in the two-wave model ($\beta_1=0.109, p<0.05$). In order to determine the validity of hypothesis 1, we reviewed the results of the unconstrained model (R2). The effect of knowledge sharing is inconsistent in different periods ($\beta_{11}=0.147, p=0.086$, while $\beta_{12}=0.072, p=0.408$). This variation undermines the robustness of hypothesis 1, and suggests that the effect of knowledge sharing on coordination is unstable.

Similar to step 1, we extracted e-mail information sharing and coordination data based on the whole e-mail dataset (78291 e-mails), and fitted the LCLP model to analyze the reciprocal relationship between information sharing and coordination. The e-mail communication network in the first period (Q3 2000) is depicted in Fig. 6. Similar to the pattern in Fig. 4, members with higher coordination scores tend to locate in the center of the network. This again corroborates the findings of Hossain [27] that coordination is more closely related to e-mail network position. The LCLP model results (R5) are listed in Table 6. The overall model fit is relatively poor, and the reciprocal relationships are not statistically rigorous. This may be attributed to the inclusion of invalid communication data. In this light, coordination is the antecedent of knowledge sharing behavior, but not the antecedent of the e-mail information sharing. This

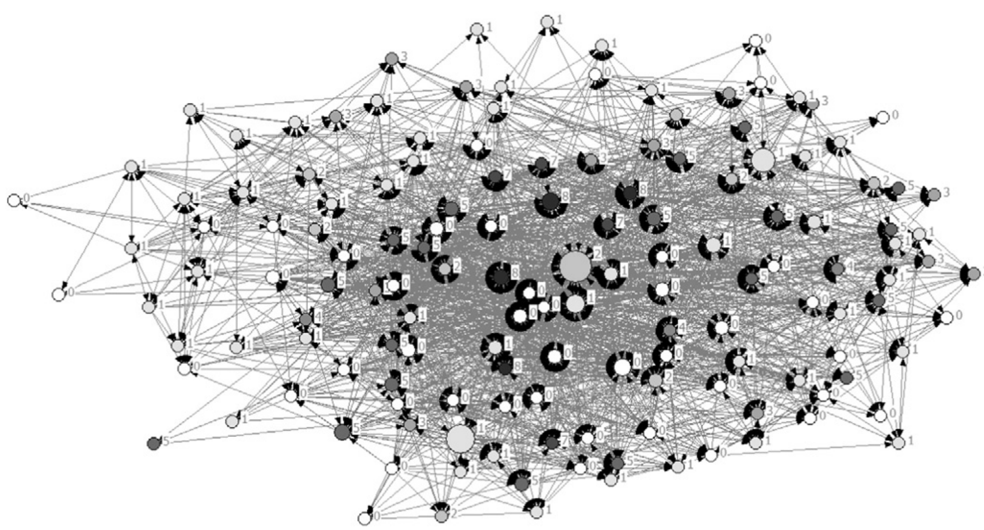

**Fig. 6.** E-mail information sharing network in the first period (Q3 2000)

**Table 3**
Key phrases indicating coordination and their weights

| Managing shared resource | Weight | Managing task/subtask dependencies | Weight |
|---|---|---|---|
| Make sure | 7.57 | We need to | 5.81 |
| I would like to | 5.49 | We should | 5.61 |
| Please do | 5.46 | I recommend | 5.52 |
| Look into | 4.91 | I want to | 4.81 |
| Please see | 4.81 | Please prepare | 4.46 |
| I want to | 4.81 | We can discuss | 4.39 |
| Help with | 4.75 | I need to | 3.91 |
| I would appreciate | 4.32 | We can then | 3.32 |
| I ask | 3.91 | Please arrange | 3.00 |
| Please get | 3.46 | I would suggest | 2.00 |
| Please allow | 3.17 | To ensure | 1.58 |
| I would like you | 2.58 | It will need | 1.58 |
| I request | 2.32 | | |
| Please arrange | 1.00 | | |
| **Managing simultaneity constraint** | **Weight** | **Managing producer/consumer relationship** | **Weight** |
| Schedule | 7.23 | Please find | 5.32 |
| Agenda | 6.95 | Please see | 4.81 |
| Due | 6.39 | FYI | 4.75 |
| On time | 5.91 | Attached is | 4.46 |
| Follow up | 4.64 | Please download | 4.17 |
| Timetable | 4.00 | For your information | 4.00 |
| Meeting | 3.91 | I provide | 2.58 |
| Submission | 3.32 | | |

distinction also indicates the difference between knowledge sharing and general e-mail information sharing.

## 5. Discussion

Drawing on the above empirical results, several theoretical and practical insights can be derived.

First, the empirical findings support the sociology perspective, while the cognition perspective is not supported in the current empirical analysis. Knowledge sharing is a necessary but not sufficient condition for coordination. Sharing common knowledge, such as technical terms, is the basis of communication and coordination. However, when the project team becomes saturated with such common knowledge and awareness, knowledge sharing cannot further improve coordination [15].

Key coordinators in the organization tend to hold central positions in knowledge sharing. From the perspective of network dynamics, more coordination behaviors in the previous period can promote the member to more central network position. This provides practical implications on how to delegate authority to project managers. Delegating authority to project managers by promoting their formal positions does not ensure their central roles in knowledge sharing [46]. Performing coordination activities is also essential for project managers [24].

Second, both knowledge sharing and coordination have strong behavioral inertia across periods, as evidenced by relatively strong auto-correlations. Knowledge sharing and coordination are continuous and stable behaviors, however, the underlying rationale may be different. Knowledge sharing is quantified as network position in this study, and represents a type of social capital which must be gradually accumulated. Coordination, on the other hand, is manifested in e-mail communications as an instant behavior. The stability of coordination reflects the stability of individual behavioral patterns [17].

The behavioral inertia explains the paradox that some knowledgeable members continue to be located at the periphery of the knowledge sharing network [8,30]. The findings of this study suggest to enhance their knowledge sharing roles by motivating coordinative activities. In this way, members' knowledge can be better exploited and shared across the organization.

Third, formal organization positions do not necessarily match the informal positions in knowledge sharing network. In traditional functional organizations, the organization hierarchy determines the coordination system and the amount of information obtained by members. Members with higher positions process more information, and play more pivotal roles in knowledge sharing. However, this no longer holds for PBOs where organization structures are more flat. Individual members are delegated with more authority, and management decisions are made in a more distributed manner to achieve flexibility to frequent changes. Communication paths spread widely across departments to integrate interdisciplinary expertise, instead of being subject to the framework of rigid organization hierarchies. Organization knowledge flows along these communication paths and diffuses across the whole network. Some members perform coordinative behaviors in managing dependencies, and spontaneously emerge as the coordinators of the knowledge sharing network.

Members themselves may not be able to accurately evaluate their roles in knowledge sharing [12,67]. This becomes even more complicated for managers based on the limited information and subjective judgments. The knowledge sharing network analysis approach in this study can be adopted by managers in practice to obtain a better understanding of organization knowledge sharing.

Fourth, knowledge sharing network is distinct from e-mail information sharing network, and includes more valid information. Plenty of redundant and invalid information exists in the unrefined e-mail dataset. Coordination is correlated with e-mail information sharing, but due to the inclusion of too much noise, the correlation is undermined and not eligible for causal inference. The refined e-mail dataset includes e-mails with higher potential to convey knowledge, and better captures the knowledge sharing behaviors. In this light, merely recording project data and information may be insufficient to enhance organization knowledge accumulation. Information should be carefully processed before being recorded in organization knowledge management systems to prevent the inclusion of noise and the information overload phenomenon.

**Table 4**
Reliability test of latent variables

| Latent variable | Cronbach's $\alpha$ | Latent variable | Cronbach's $\alpha$ |
|---|---|---|---|
| Knowledge sharing 1 | 0.794 | Coordination 1 | 0.964 |
| Knowledge sharing 2 | 0.813 | Coordination 2 | 0.934 |
| Knowledge sharing 3 | 0.780 | Coordination 3 | 0.940 |

**Table 5**
Model fit indices of the three models

| Model | $\chi^2$ | *df* | Model fit indices | | | |
|---|---|---|---|---|---|---|
| | | | TLI | CFI | RMSEA | SRMR |
| R1. Baseline | 412.747 | 286 | 0.95 | 0.95 | 0.055 | 0.131 |
| R2. Unconstrained | 377.155 | 270 | 0.96 | 0.96 | 0.052 | 0.036 |
| R3. Target | 399.885 | 284 | 0.95 | 0.95 | 0.053 | 0.029 |

**Note:** TLI (Tucker-Lewis Index) and CFI (Comparative Fit Index) are equal to 1 for perfect model fit; RMSEA (Root Mean Square Error of Approximation) and SRMR (Standardized Root Mean square Residual) of 0 indicate perfect model fit. All these model fit indices range from 0 to 1.

## 6. Conclusions and future studies

This study investigates the causal relationship between knowledge sharing and coordination with empirical analysis on the Enron dataset. The sociological perspective is supported in the current empirical analysis in that coordination conduces to knowledge sharing, while knowledge sharing in turn does not have salient contribution to coordination. Based on these findings, construction PBO managers can improve knowledge sharing by effective coordination, and align members' knowledge sharing roles with their abilities.

Following the quest for adopting mixed methods in construction management studies [74], several methods are combined to compensate each other. By SNA and text mining methods, we derived the indicators of the two constructs but also included measurement errors. SEM compensates for this disadvantage by allowing for measurement errors. The large sample size required by SEM is in turn conveniently satisfied by the SNA and text mining methods. For instance, if the knowledge sharing network data of the 147 members were obtained by interviews, we need to investigate $C_{147}^{2} = 10731$ pairs of potential knowledge sharing ties for each period. This involves great effort (if not practically infeasible), not to mention the subjective bias and the difficulty for interviewees in recalling the numerous knowledge sharing ties [13,27,67]. Knowledge sharing and coordination are two abstract constructs difficult to quantify in practice. The combination of SNA, text mining and SEM methods adds measurable and tangible dimensions to the subjective topic of knowledge sharing and coordination from an analytical point of view. Future studies can utilize the analysis approach in other contexts.

The implications of this study should be viewed with respect to its limitations, which point to several directions for future studies.

This study aims to investigate the relationship between knowledge sharing and coordination at the individual level, and the organization members are the units of analysis. The empirical results suggest that the variance of knowledge sharing is explained by the variance of coordination. In view of the fact that individual members behave heterogeneously, the findings indicate that the causal relationship is a common pattern in this organization context. However, since only one construction PBO was analyzed, some organization level variables were controlled and hence not analyzed. These variables may act as important moderators or mediators of the causal relationship. For example, trust among members is the consequence of effective coordination and the antecedent of knowledge sharing [5,9]. It may be a mediator of the relationship between knowledge sharing and coordination.

**Table 6**
The results of the robustness tests

| Model | $\chi^2$ | *df* | Model fit indices | | | Path coefficients | | |
|---|---|---|---|---|---|---|---|---|
| | | | TLI | CFI | RMSEA | SRMR | $\beta_1$ | $\beta_2$ |
| R3.Target | 412.747 | 286 | 0.95 | 0.95 | 0.055 | 0.131 | 0.117 | 0.315** |
| R4.Two-wave | 165.649 | 117 | 0.91 | 0.92 | 0.053 | 0.060 | 0.109* | 0.292** |
| R5.Information | 660.776 | 284 | 0.72 | 0.73 | 0.095 | 0.109 | 0.145* | 0.122* |

Note: *denotes $p<0.05$, **denotes $p<0.01$.

Also, project attributes may moderate the causal relationship, since, in more complex projects, knowledge sharing may become more fundamental to coordinating interdisciplinary expertise. Thus, although it is not uncommon for SNA studies to be built on a single organization [11,13,27,29,35,80], future studies are needed to test the generalizability of the findings by empirical study in other organization contexts or by cross-organization comparison.

The e-mails with external project participants were not included in the analysis procedure to focus on internal organization coordination and knowledge sharing. However, construction PBOs rely heavily on the relationships with external partners in delivering projects. When including external links in the network, the network positions and coordination behaviors of some members may change. For example, some peripheral members may become the important "gatekeepers" exchanging knowledge with external nodes [80]; some members may perform more coordinative roles in managing dependencies with external project participants. It would be interesting for future studies to investigate the coordination and knowledge sharing activities across organization boundaries.

The indicators of knowledge sharing are slightly positively skewed. The LCLP model achieved a relatively poor model fit compared to studies with a similar sample size. Again, this problem probably originates from the specific dataset we analyzed. Future studies are needed to generalize the analysis procedure in other contexts and obtain more robust findings. Moreover, knowledge sharing relationships are approximated only by e-mail thread communications. Future studies may combine this approach with interview or questionnaire data to better capture knowledge sharing behaviors.

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## Appendix A. Examples of key phrase annotation

As elaborated above, we identified coordination behaviors by key phrases. The following examples are presented to illustrate how we annotated the key phrases and calculated the coordination scores for each member.

**Example 1.** a coordinative e-mail with key phrases

In Jan 2001, the vice president John Arnold sent an e-mail (Message-ID: 27034451) to managing director John Griffith:

"*John:* ***I would like you*** *to come talk to a couple more people on the gas floor about a possible position down the road. My assistant Ina Rangle is going to* ***schedule*** *a couple interviews. Please coordinate with her.*"

The highlighted word "I would like you" indicates the activity of managing shared resource (John Griffith as the managing director of several projects), and "schedule" indicates the management of simultaneous time constraint.

According to Table 3, in this e-mail, John Arnold scored 2.58 in managing shared resource, and 7.23 in managing simultaneity constraint. Similar analysis procedure can be applied to each e-mail with the help of an Excel VBA computer program.

**Example 2.** a coordinative e-mail without key phrases

The key phrases have good predictive power, whereas there are still e-mails embodying coordination without the key phrases. For example, in Nov 2000, managing director John Hodge sent his staff Bradley Mckay an e-mail (Message-ID: 19296869):

> "*Could you please update this spread sheet with the products you would like to offer on a new version of EOL. Please e-mail me your additions and changes and I will consolidate everything into a presentable format.*"

By this e-mail, John Hodge clarified that Bradley Mckay's update to the spreadsheet would act as the input to his later work. The management of producer/consumer relationship was expressed without using the key phrases in Table 1. In fact, there may be infinite ways to convey coordinative messages, and inevitably, some of them may be missed by the finite collection of key phrases. As indicated by the performance of SVM models based on the key phrases, the key phrases can capture most of the coordination behaviors.

**Example 3.** a non-coordinative e-mail with key phrases

In Nov 2000, manager Stephanie Harris sent lawyer James Derrick an e-mail (Message-ID: 75846291) about the negotiation with the local government:

> "*Please note that the changes indicate that Phase **I need to** be reviewed by Maharashtra Gov't, so the early reports should be revised. Please confirm it and review the related agreements.*"

The key phrase "I need to" is misidentified from the phrases "phase I" and "need to", and do not reflect any coordination behavior at all. Since the key phrases may express different meanings within different contexts and sometimes may even be misidentified, such errors may occur. Based on the SVM model results, we are confident that such errors are not substantial.

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