Location-based measurement and visualization for interdependence network on construction sites

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Abstract

Appropriately assigning workers to tasks is vitally important in project management. To do this, project managers need to objectively and effectively measure and visualize the spatiotemporal orders of real construction process as well as coordination structure of the workforce. However, currently there is no method/tool available to project managers to represent spatiotemporal orders of construction processes. To address this issue, this paper presents a novel approach to measuring the real spatiotemporal order of onsite tasks as well as the task interdependence by an interdependence network. This approach extracts the distance of workspace distributions as a key interdependence indicator from historical location tracks across different construction stages according to the area-restricted nature of construction activities. It then integrates generated interdependence into a network over time, to imply the cooperation patterns in stages and a task delivery across stages with a holistic view. To validate the approach, location data were collected from 31 workers working in a high-rise housing construction project for one week to construct the interdependence network of this project, which was used to quantitatively evaluate the performance of construction schedule, assignments and cooperation. Results show that the interdependence network is able to provide insightful information on how

workers perform individual tasks onsite and it is also an effective tool to identify and display the interactions among site workers.

Keywords

Construction activities, interdependence network, quantitative measurement, location-based service.

1. Introduction

A crucial issue in construction industry - which is typically labor intensive – is whether construction workers are assigned with suitable tasks. Task assignment not only influences project performances, but also the safety and wellbeing of worker themselves. As a part of a construction plan, a construction schedule is commonly predefined ahead of the real construction. The schedule serves as a basis in assigning individual tasks to the workforce. However, when individual workers cannot complete their assigned tasks in time, the whole project is prone to delay due to workspace occupancy and spatiotemporal interdependence of tasks [1, 2].

On the other hand, project managers do not have effective tools to conveniently track and represent workspace occupancy and dynamic interchanges of workforce on sites. Direct observations and daily/weekly reports often lead to inefficiencies in identifying and resolving conflicts in spatiotemporal interdependence of tasks. This study thus aims to develop an interdependence network to explicitly track and represent spatiotemporal interdependence of construction tasks [3]. The interdependence network is automatically generated from site information collected by a real-time location system; and this independence network has the potential to become an effective tool for project managers in analyzing and resolving spatiotemporal conflicts of construction tasks.

Unlike in the manufacture industry where products are assembled on a production line by workers whose working locations are relatively static, building components are static in locations where different trades of workers come to execute different tasks at various time periods [4]. Thus the location of workers does not only indicate the distribution of workspace occupied by workers, but also represent the sequence of carrying out construction tasks by workers [5, 6]. In addition, since workspace is a limited resource, how to allocate workspace among workers implies how workforce collaborates to conduct a collaborative task. Visualizing the variation of workspaces among workers enables project managers to identify potential spatiotemporal conflicts within the process as well as obtain feedback from workers on task assignment.

2. Background, related work and assumptions

As a relevant concept to this study, social network is widely adopted as it can integrate social variables to represent construction process and the workforce organization [7-11], acknowledging that enhanced communications and knowledge sharing can achieve better project performances [12, 13]. Through surveys including questionnaires and interviews, a generated social network visualizes and represents interactions among stake holders. However, indirectly obtaining sufficient information and knowledge through questionnaires and interviews can be tedious and troublesome. In addition, a social network can only represent qualitative and non-temporal values; these largely prohibited us to directly adopt social network to visualize spatiotemporal interdependence of construction tasks [14, 15].

In this study, a novel network is developed to measure and visualize construction processes and workforce organization in terms of their area/space-restricted and temporal natures. According to the coordination theory, interdependence of construction tasks is classified into three categories: pooled, sequential and reciprocal interdependence. *Pooled interdependence* refers to two tasks/workers where "one (task) in which each part renders a discrete contribution to the whole (of another task) and each is supported by the whole (of another)" [16-18]. This type of interdependence usually appears when a construction assignment is allocated by areas in which the assignment is the linear combination of individual tasks. *Sequential interdependence* describes the interdependence of two tasks/workers where "the previous one must act properly before the next; and unless the previous one acts, the next one cannot solve its output problem" [17]. Sequential interdependence is common as construction schedules are typically developed according to a specific logical sequence to facilitate the completion of tasks in chronological order. *Reciprocal interdependence* refers to the interdependence of two tasks/workers "in which the outputs of each become inputs for the others" [17]. This type of interdependence is also familiar in construction industry. For example, if two rebar workers are assigned to do different shifts, one of them completes a shift and goes home; while another comes to continue the task in his shift. A common feature of these three types of interdependence is the same: if one worker fails to accomplish his task, the productivity of entire team degrades. However, each type of interdependence has different effects on the project progress. Specifically, workers with pooled interdependence are able to conduct individual tasks independently, workers with reciprocal interdependence are interlocked and their productivities are interactively affected by each other, workers with sequential interdependence often cannot commence their tasks on time. Identifying these types of interdependence will enable managers to re-consider the implications in assigning workers in proper assignment at right time slots, so as to avoid any potential negative effects.

Due to the area-restricted nature of construction assignment, this study utilizes locations of workers to directly derive the interdependence from measurements [19]. The spatiotemporal locations of each worker can be collected by various monitoring systems, such as real-time location system (RTLS) and camera surveillance system around the construction sites [20-24]. There have been various studies to utilize RTLS to measure if the proximity between workers and hazardous regions exceeds the allowable threshold, and to identify workspaces concurrently occupied multiple both workers and equipment which is an evidence of conflicts and congestions [25-28]. However, major manual tasks on sites demand collaboration in physical proximity, leading to false alarms and work interruptions [29-32].

In order to realistically reflect how workspaces are utilized in construction projects, this study specifies that workers in reciprocal interdependence can share the same workspace at the same time; and workers in sequential interdependence can share the same workspace at different time; while workers in pooled interdependence cannot share the same workspace anytime. A schematic illustration of the three types of interdependence and their corresponding workspace sharing scenarios is demonstrated in Fig. 1.

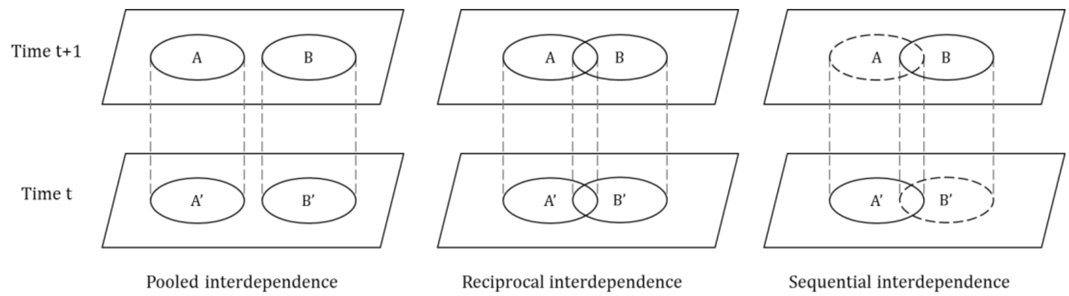


Fig. 1 The schematic diagram of various interdependence and workspace sharing scenarios

To derive the interdependence level from workers' trajectories and workspace uses, a quantitative method is developed based on the following assumptions:

- The topological distance between workspaces can be considered as an indicator for interdependence relationships. This assumption stems from the fact that to cooperate with each other on construction sites, workers have to be in physical proximity.
- Workspace considered in this study is assumed to be open space occupied by workers for direct manual works, not for work breaks, preparation works, etc. For example, crane operation does not have the area-restricted characteristic since operators can manipulate away from building components. Therefore, movements of workers in the trajectories data have to be filtered by observation or an automatic model – switching state-space model [33].
- Workers are classified by trades: each worker is capable of doing one type of tasks with the same skill level.

Based on these assumptions, an interdependence network can be generated to objectively and graphically represent the spatiotemporal relationships of workspaces by the method elaborated subsequently.

3. Key steps to construct the interdependence network

The proposed method contains three key steps, listed as follows:

Step 1: Construct a heat map from location tracks

This step is to extract a bivariate histogram based on the distribution of individual worker's trajectory in unit time, associated with a specific task.

Generating a quantitative representation of workspaces is a challenging issue. Previous studies suggested that a discrete matrix is an effective representation of workspaces [34, 35]. Heat/density map is defined here as the mathematical base of workspace of unit personnel, describing the distribution of workers in executing a construction activity measured by real-time location systems [35-38]. To construct such a map, the entire construction site is divided into chessboard-like 2D grids. The number of location points falling into each non-overlapping cell is hence embedded into the matrix. Fig. 2 provides a heat map example for the pipe installation by plumbers. In addition, the number in a specific cell indicates the frequency of the plumber's entries into that cell.

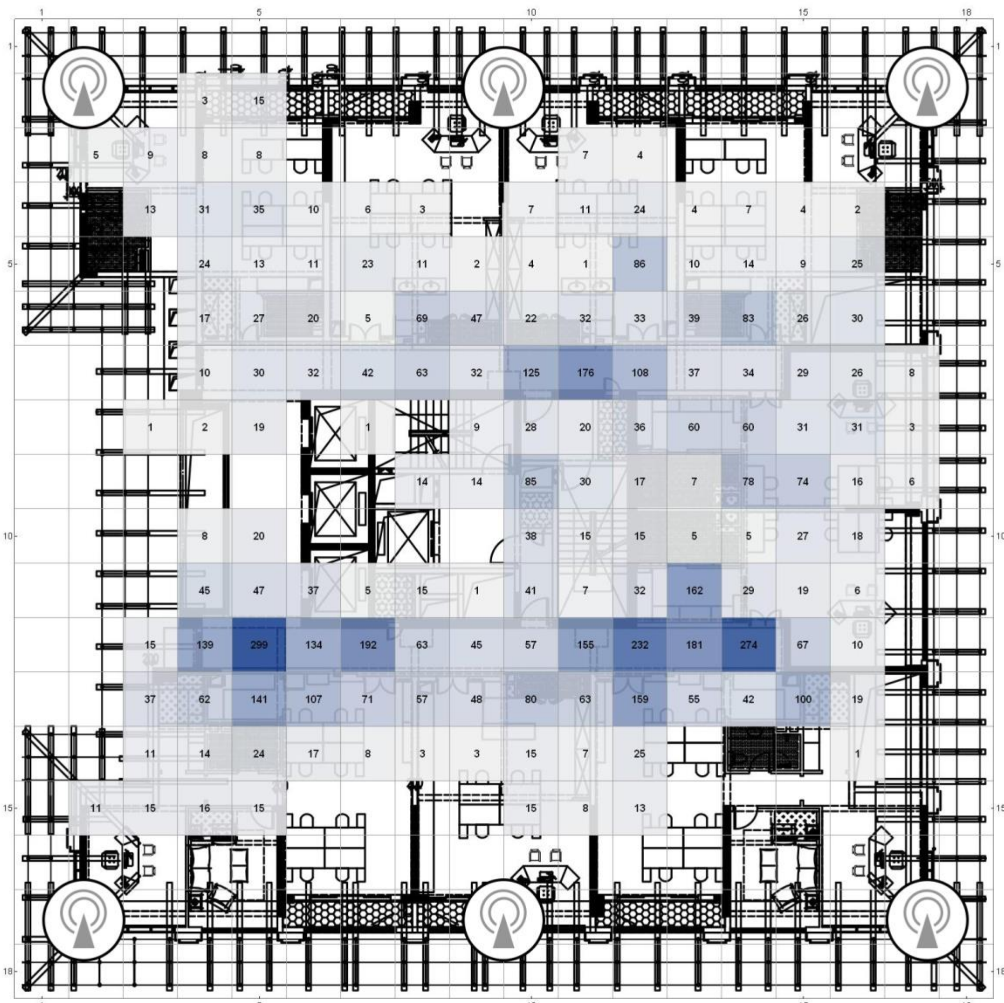


Fig. 2 The heat map of workspace

A key issue in this process is to determine the dimension of grids, which affects the representation of workspace distribution and computational time needed to construct the interdependence network. In previous studies, a *9 m × 9 m* grid was selected for earthmoving operations [34]; a *3 m × 3 m* for trucks [35] and *0.5 m × 0.5 m* for workplace requirements analysis of labors respectively [37]. Although smaller grids ensure a higher accuracy of tracking, the acceptable grid for labors in this paper is identified as *2 m × 2 m* since this study focuses on the distribution of workspace rather than behaviors of workers. Of course, a finer grid can be adopted for analysis if it deems necessary. On the other hand, selecting a $2\ m \times 2\ m$ ensures that all location-fixed activities can be recorded without area gaps due to the fact the average workers' arm span is *181.7 cm* [39].

Heat map is a simple and visual representation of space occupied by workers that not only contains the boundary but also the distribution of workspace. The element with relatively high value represents that greater efforts are devoted to the activity in the corresponding cell, indicating that the task in that cell demands more working hours.

Step 2: Compute the level of interdependence between workspaces

Graphical distances between heat maps of unit personnel are measured to describe the level of interdependence matrix to facilitate clustering phylogenetic analyses. Distance is defined as a numerical description of how far two objects are geographically apart, while similarity is an indicator describing how close between two objects. Table in the appendix lists popular methods measuring distance and similarity [40, 41]. To simplify the computational process as well as avoid calculation overflow, consider the smallest distance as zero while the biggest distance as one. Since Binary Jaccard distance (BJD) is a robust and efficient estimation where the collected data contain incessant noises due to inadequate accuracy of current RTLS, and the computation time is also saved by Boolean operation, this study employs BJD as an indicator of interdependence between workspaces to describe the relationship between workers, which can be represented as:

$$\text{Binary Jaccard distance} = \frac{|X \cup Y| - |X \cap Y|}{|X \cup Y|}$$

where X and Y represent the vectors derived from flattening bivariate histograms of two workers respectively. Notably, taking BJD as an example to show the analysis progress does not mean other computational methods are not feasible, the remaining measurements can also be used where location tracks are generated accurately.

Interdependence index is defined as the parameter indicating the strength of interdependence between a pair of workers, which can be computed by subtracting the distance from unit one. To gain a holistic insight into the patterns of population, interdependence matrix is then proposed resembling relationship matrix which is a spreadsheet display of relationships between individuals. Embedded element (i, j) represents the level of interdependence between the worker (i) and worker (j). If the matrix is extracted from the same group, it is obvious that the interdependence matrix is symmetric with ones at the diagonal line. The reason is that the indices on diagonal line indicate the highest interdependence between a worker and himself. Such matrix shows the proportion of workspace occupied by each pair of workers, suggesting the reciprocal interdependence among workers. If the workers are from adjacent construction stages; the interdependence matrix is used to illustrate the task delivery from the worker at row i to the worker at column j in the matrix, suggesting how much workspace is transferred from worker (i) to worker (j) as well as the strength of sequential interdependence. More remarkably, elements with smaller values in both matrixes denoting pooled interdependence that allocated assignment of worker are separated while have small intersections on the boundaries.

Step 3: Construct and visualize the interdependence network

The interdependence network is represented in a graph which comprises a set of vertices connected by directional and unidirectional curves in 2D or 3D. A vertex in the graph, referring to the node in network, represents unit personnel engaged in the construction project. Lines stand for reciprocal interdependence while dashed lines for pooled interdependence and directional lines for sequential interdependence. Commonly, non-directional edges connected workers from intra-groups and directional edges linked workers from inter-groups, since intra-group members tend to conduct collaborative tasks at the same time, suggesting reciprocal and pooled interdependence while inter-group members at different times, suggesting sequential interdependence. However, multiple and complicated interdependence may appear once construction stages overlap.

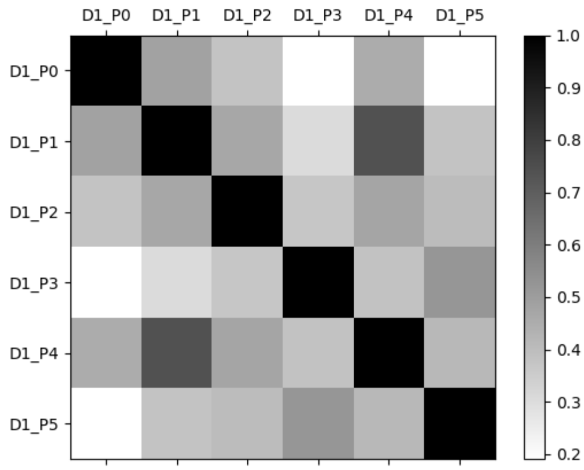
4. Case study

To examine the validity of the interdependence network, a multi-story building project in Shenzhen was used to demonstrate the proposed method. With the support of the project management, a team of 7 plumbers, 4 welders, 8 masons, 6 steel fixers and 6 carpenters involving in a series of construction activities of a complete floor was selected to collect relevant spatiotemporal data. The authors explained the experiment to the workers to obtain their informed consent and cooperation and their participation in the research as experimental subjects were voluntary. To simplify the computational progress and decrease the negative impacts on workers normal activities, the manual tasks are tracked two hours per day for a week, composed of piping installation, floor concrete placement, wall reinforcement, and wall concrete framework.

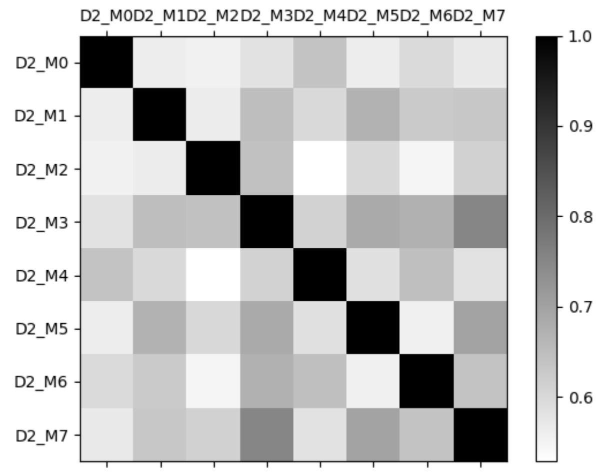
RTLS utilized for location tracking in this case was named Proactive Construction Management System (PCMS) [42], containing six anchors deployed on scaffoldings around the typical floor (refer to detailed deployment in Fig. 2) and a wireless receiver connected to the workstation. Identification tags were attached to the helmets of the above workers involved in onsite construction activities in the 28th floor. Compared with GPS and other outdoor location systems, PCMS was more accurate and adjustable in small outdoor regions as the theoretical accuracy and tolerance using the time of flight (TOF) was within 3 meter radius of real positions [43]. However the real-time location system may fail to achieve the theoretical accuracy facing ambient occlusions and excessive workers. Consider this, before and in this experiment, the authors calibrated PCMS by three points with fixed distances and adjusted the moving trajectories of some workers from site observation manually to ensure that the workspace distribution was tracked accurately.

4.1. Computation of the level of interdependence between workspaces

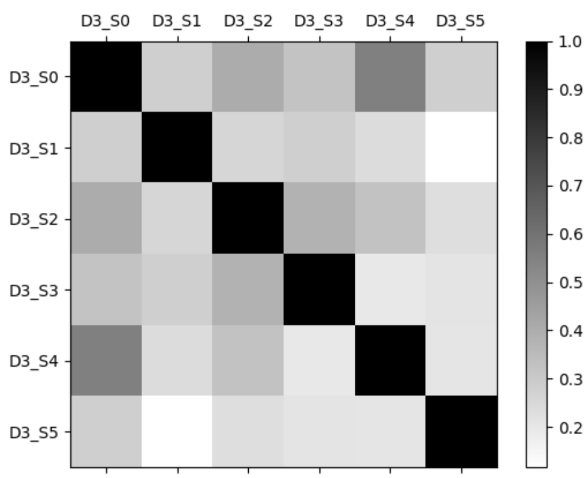
In the experiment, relevant data was collected and adopted to construct heat maps (see Fig. 2) and compute the interdependence of the above workers' workspaces.



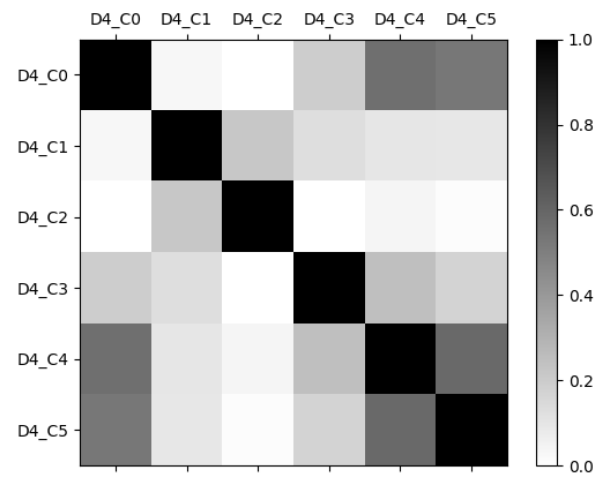
(a) Plumbers



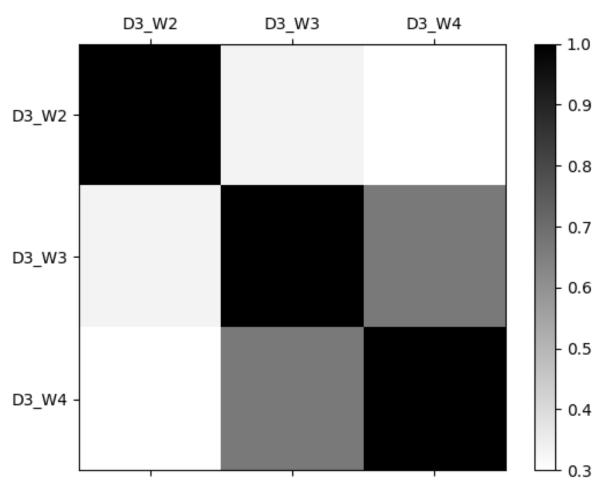
(b) Masons



(c) Steel fixers

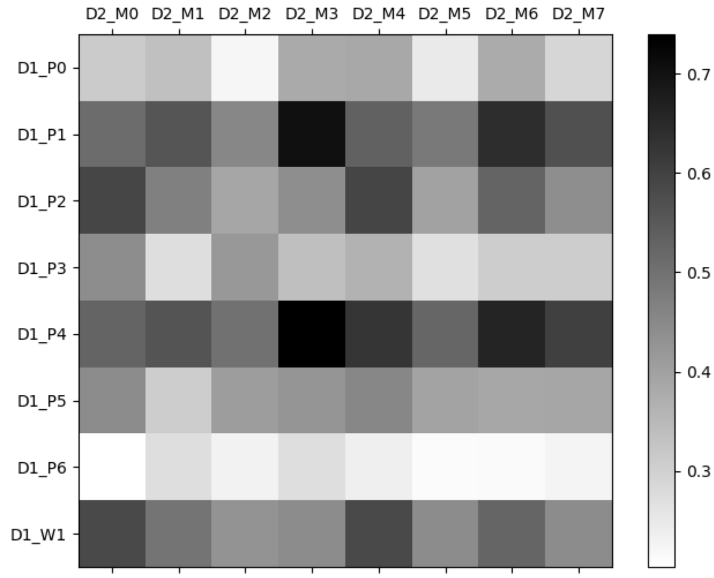


(d) Carpenters

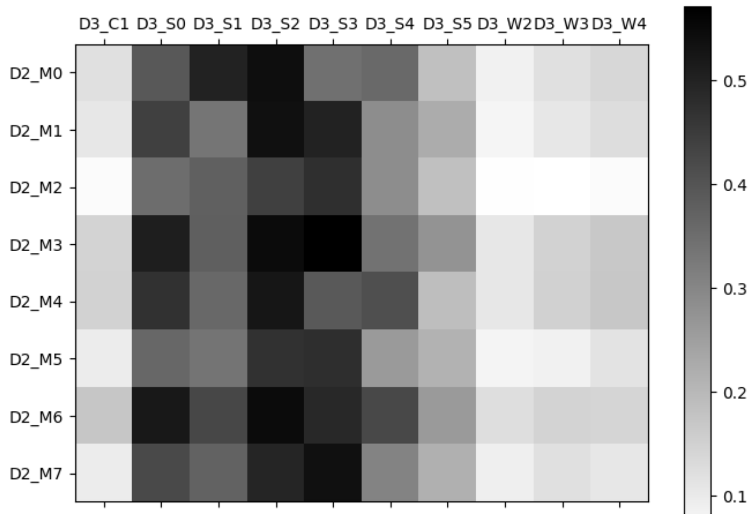


(e) Welders

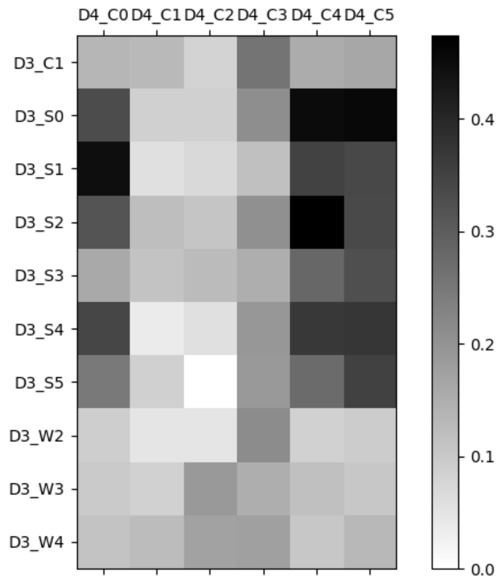
Fig. 3 The generated interdependence matrixes between intra-group workers



(a) Plumbers and masons



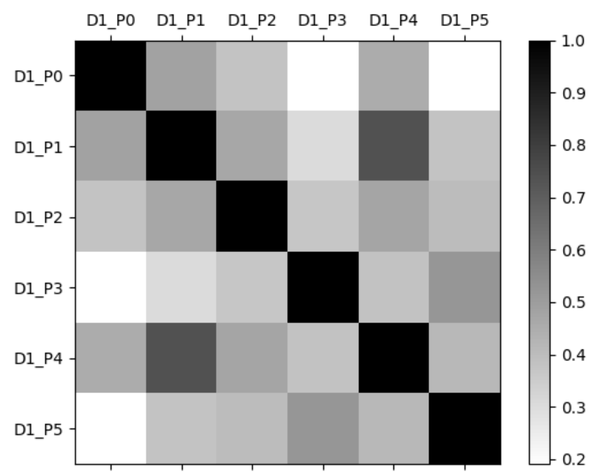
(b) Masons and steel fixers



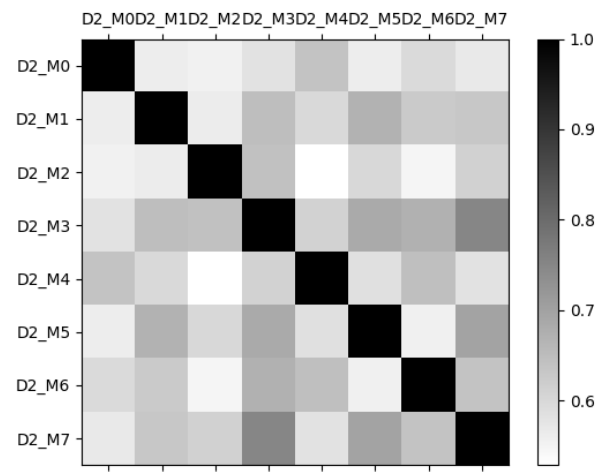
(c) Steel fixers and carpenters

Fig. 4 The generated interdependence matrixes between inter-group workers

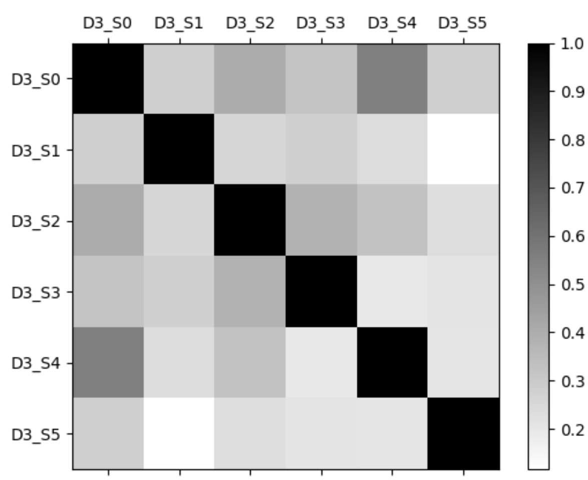
shows the generated interdependence matrixes between intra-group workers by Binary Jaccard distance. The rows and columns show the tag numbers of plumbers (P0 – P5), masons (M0 – M7), steel fixers (S0 – S5), carpenters (C0 – C5), and welders (W1 – W4) from the 1st day to the 4th day (D1 – D4). Specifically, number *zero* denotes the group leader. The gray level of each cell in the grids represents the level of pooled or sequential interdependence. More gray a cell is, higher the level of interdependence is; vice versa. Similarly, the interdependence matrixes between inter-group workers showing reciprocal interdependence were also generated and plotted (see Fig. 4). It can be seen that such matrixes facilitate the visualization of the interdependence of workspace.



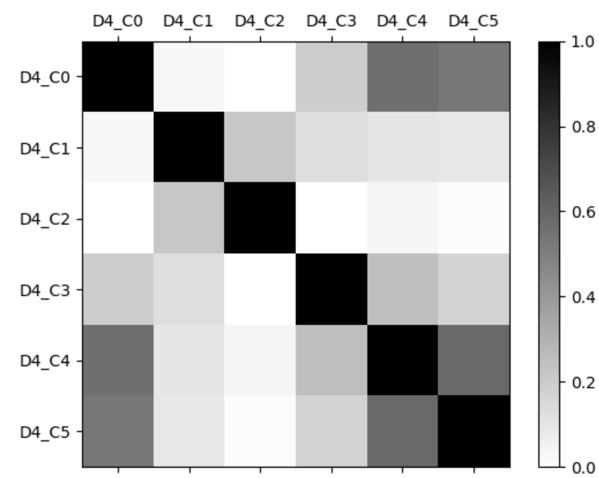
(a) Plumbers



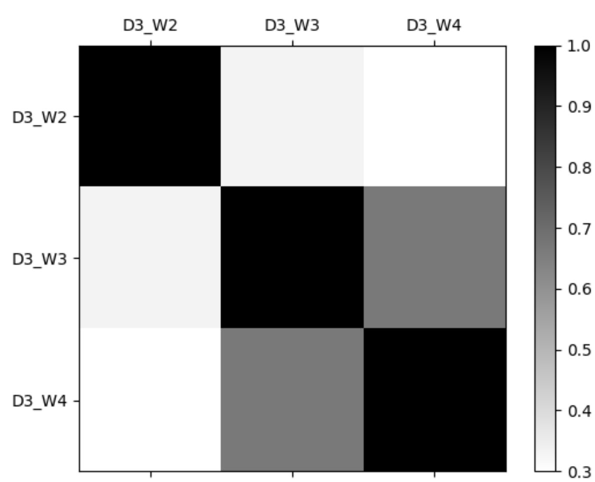
(b) Masons



(c) Steel fixers

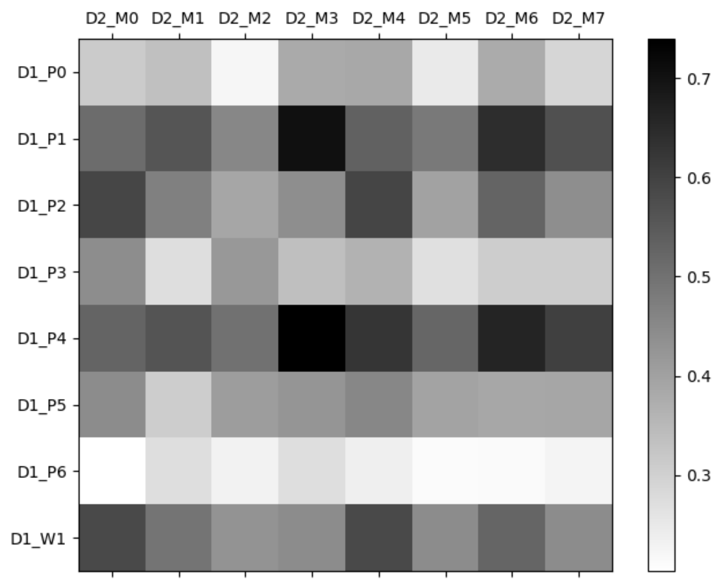


(d) Carpenters

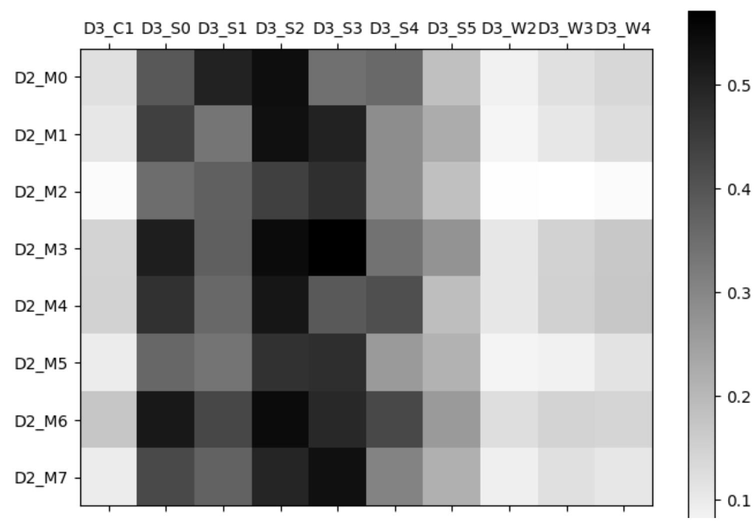


(e) Welders

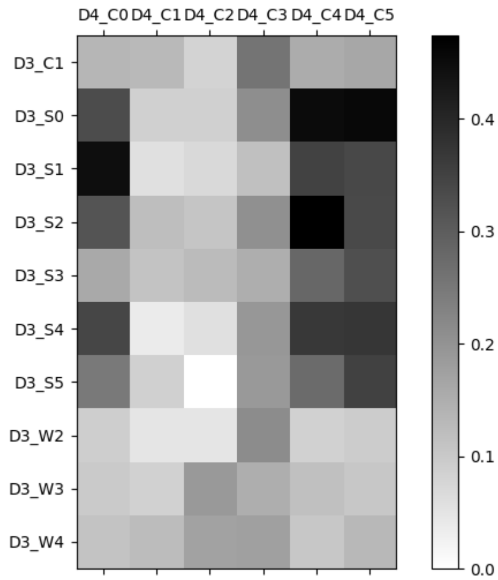
Fig. 3 The generated interdependence matrixes between intra-group workers



(a) Plumbers and masons



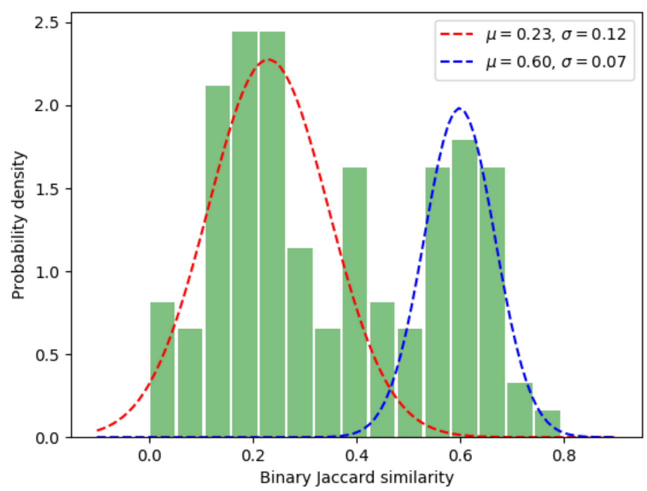
(b) Masons and steel fixers



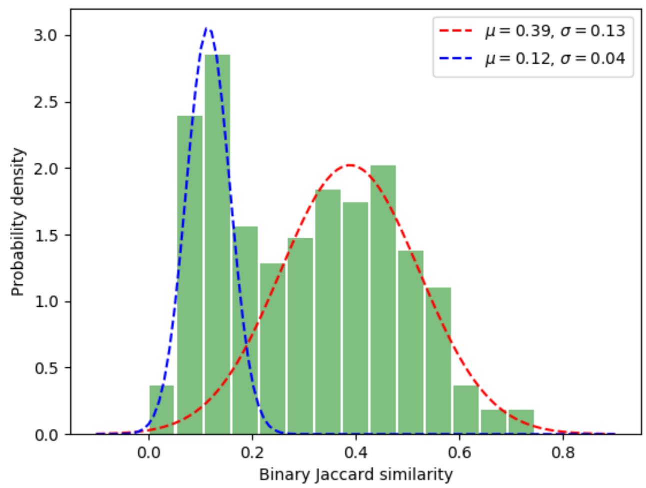
(c) Steel fixers and carpenters

Fig. 4 The generated interdependence matrixes between inter-group workers

Accordingly, the histograms of interdependence were produced within days or between days (see Fig. 5). A consistent finding is that the distribution of interdependence within days and between days follows 1D Gaussian mixture models with two components. Through the expectation-maximization (EM) algorithm, the means of small and large interdependence within days are 0.23 and 0.60 respectively with the covariance of 0.12 and 0.07 (see Fig. 5 (a)); meanwhile the means of small and large interdependence between days are 0.12 and 0.39 respectively with the covariance of 0.04 and 0.13 (see Fig. 5 (b)). Since the mean and standard deviation of interdependence remain constant along the entire construction process and the difference follows Gaussian distribution, the authors suggested to map from each component to a specific interdependence. Commonly, the pooled interdependent workers have small intersections of workspaces on boundaries at the same construction stage, in terms of that the level of interdependence is low within days; the reciprocal interdependent workers have large intersections of workspaces at the same construction stage, in terms of that the level of interdependence is high within days; while the workers with sequential interdependence have overlaps of workspaces across different construction stages, in terms of that the level of interdependence is positive between days. Therefore, the small component within days is mapped to pooled interdependence, the large component within days to reciprocal interdependence, and positive component between days to sequential interdependence. To infer the true interdependence with respect to the whole population, it is necessary to establish 95% confidence intervals around the stable means. In the case of this project, the lower limits and upper limits for pooled interdependence and reciprocal interdependence were (0, 0.53) and (0.50, 0.70) respectively, while that for sequential interdependence were (0, 1).



(a) Within days (pooled and reciprocal)



(b) Between days (sequential)

Fig. 5 The histograms of interdependence

4.2. Generation of the interdependence network

Based on the above level of interdependence, the crucial interdependences were extracted and highlighted, the interdependence networks yielded. Fig. 6 shows the interdependence network within days. As Fig. 6 (a) illustrates, 7 plumbers and 1 welder were in charge of piping installation on the 1st day. Except P1 and P4, the remaining workers were fully connected by pooled interdependence or reciprocal interdependence. There were only three reciprocal interdependence between P3 and P5, P5 and W1, as well as W1 and P2, suggesting that the plumbers were allocated by areas on the 1st day to conduct the piping installation tasks, and the welder made significant contributions to plumber 2's and plumber 5's tasks. The group leader – plumber 0 – held pooled interdependence with the other group members, implying that the task allocation of piping installation by area was suitable for plumber group.

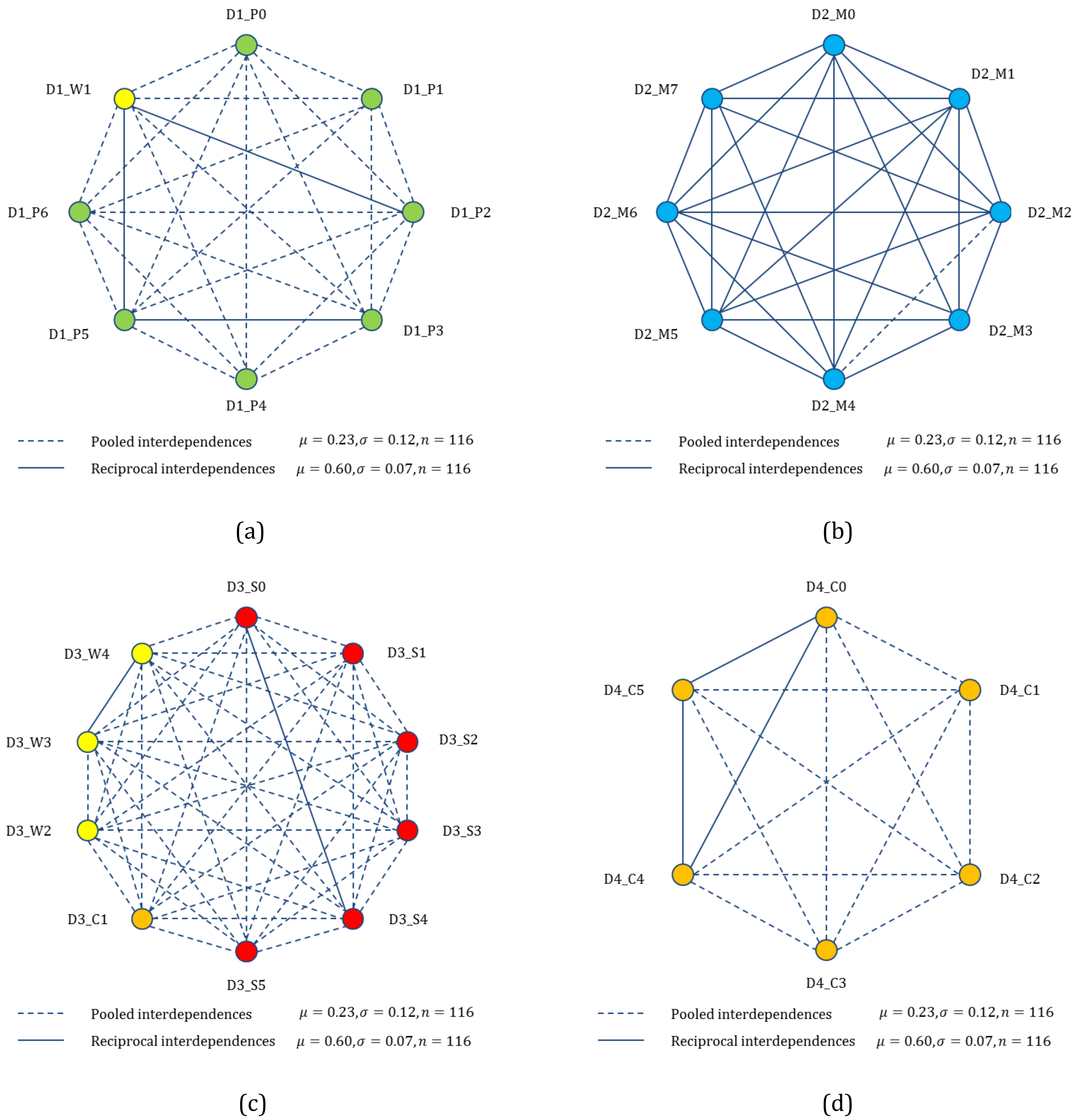


Fig. 6 The interdependence network within days

As shown in Fig. 6 (b), 8 masons completed the concrete placement of the typical floor on the 2nd day. Almost all of them were connected by reciprocal interdependence, revealing a different task allocation pattern for piping installation. The reason was that the masons collaborated with each other where concrete was poured before hardening, and then moved to the next position after vibration and smoothing. Thus, the spatiotemporal relationships of workspaces were more comprehensive and complicated. Here, mason 0 was connected with all masons, proving strong leadership in the group.

Fig. 6 (c) shows multiple workers on the 3rd day, containing 6 steel fixers for wall reinforcement, 3 welders for concrete bar welding and a carpenter for concrete formwork removal. Similar to the plumbers, most of the links were dashed lines, indicating that the main task of wall reinforcement was allocated by areas where workers were able to carry out the tasks individually at the same time. In addition, the steel fixers were fully connected with the welders, offering necessary assists in the combination and enhancement of steel components.

It can be seen from Fig. 6 (d) that the 6 carpenters participated into the installation of wall concrete framework. C0, C4 and C5 were connected by reciprocal interdependence while others were connected with pooled interdependence. This implied that the main tasks were allocated to individual carpenters by areas while the other tasks were allocated to a subgroup of carpenters by building components.

In summary, the networks show that the workers were allocated with construction tasks by areas or components. Pooled interdependence and reciprocal interdependence connected intra-group workers and assembled their works into comprehensive building products. From the structural networks, managers could directly identify the roles that a worker was played within a group and obtain feedback from the worker daily/weekly.

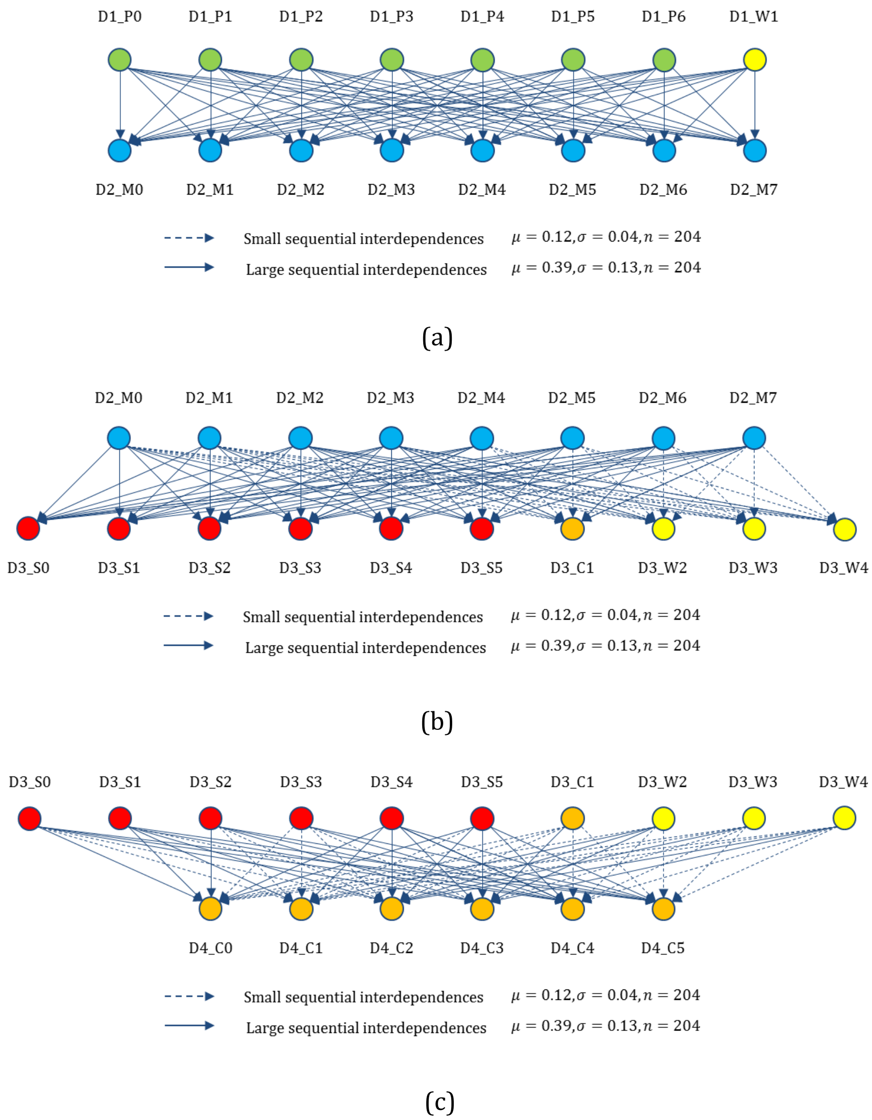


Fig. 7 The interdependence network between days

On the other hand, the interdependence networks between days were also built to mainly describing the sequential interdependence by considering adjacent construction groups across construction stages (see Fig. 7).

Fig. 7 (a) shows, the sequential interdependence between the plumber and the masons, that is the masons conducted floor concrete placement after floor piping installation by the plumbers. Since the collaboration pattern of masons was comprehensive, almost the task of each plumber had an impact on the task of each mason. That's why the major sequential interdependence was large from the Day 1 to Day 2. But in Fig. 7 (b), more small sequential interdependence appeared in the interdependence network from Day 2 to Day 3. Notably, most of the dashed arrows were connected to the welders, suggesting that the welders as the supporters contributing to wall reinforcement tasks. Analogously, most of the small interdependence from the welders in the interdependence network from Day 3 to Day 4 (see Fig. 7 (c)).

The inter-group interdependence networks from adjacent days mainly showed the sequential interdependence. Most of the sequential interdependence was strong since limited space resources on construction sites had to be reused across construction stages; while weak sequential interdependence mainly connected from/to the supporters who displayed as glue to integrate the other members of the groups. This type of structural networks visually revealed the spatiotemporal order and construction task delivery at the individual level, providing the managers a tool for comparison of real construction process and construction plan.

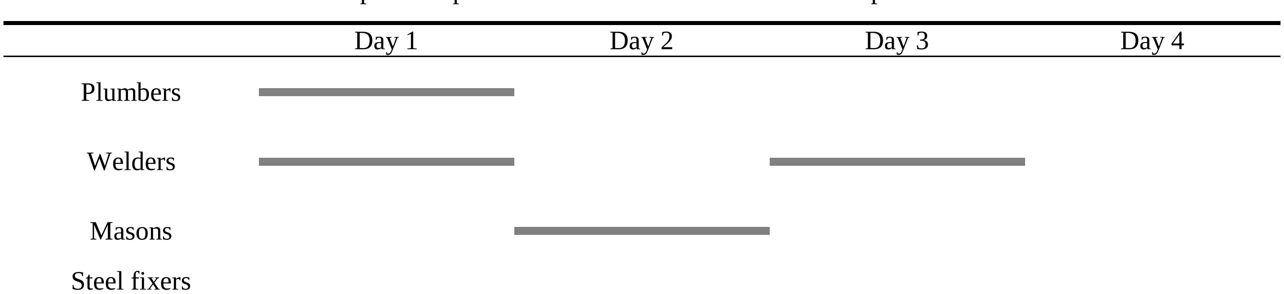
5. Performance evaluation

To further illustrate the usefulness of the proposed interdependence network, the network-based quantitative performance evaluation of the above project was conducted, mainly focusing on construction schedule and construction assignments and cooperation.

5.1. Evaluation of construction schedule

Construction schedule provides a spatiotemporal order and working patterns of construction tasks. If all workers stick to the schedule, managers enable the construction process to be under control and fulfill the quality and quantity requirements in time. According to the real construction progress of the above project, there were no overlaps between construction stages, it meant that there should be only one group on construction site per day to finish one specific task. For example, plumbers, masons and steel fixers only conducted their tasks on specific days to avoid physical congestions and collisions with other workers. Specifically, the welders as supporters were assigned with both piping installation and concrete bar welding tasks, it was necessary for the welders to engage in the tasks of Day 1 and Day 3 (see Table 1) according to the generated interdependence networks. However, concrete formwork was installed on Day 3 by the carpenters, who were supposed to begin their works on Day 4. This task was carried out ahead of normal schedule, leading to extra workers, potential congestions and collisions of workspaces. Such unreasonable use of limited workspace on construction sites might cause productivity decrease or safety issues. Through the visual interdependence network, managers could directly identify the unreasonable process – carpenter 1 in Fig. 6 (c) – and made a decision to revise the schedule based on the feedback of workers.

Table 1. The spatiotemporal order of workers from the interdependence networks



Carpenters	

5.2. Evaluation of construction assignment and cooperation

The unreasonable use of limited workspace on construction sites is usually caused by unreasonable assignment or cooperation issues. Interdependence networks offer a holistic view on the use of workspace and workforce organization on construction sites. By quantitative analysis, this view enables managers to identify the lags in the workforce organization and task allocation. In this case, according to the generated interdependence networks, the realistic interdependence, which did exist among workers and across construction stages, was summarized in Table 2.

Table 2. The realistic interdependence among workers

<table>
<tr><th rowspan="2">Workers</th><th rowspan="2">Stages</th><th colspan="3">Comparison with fully connected networks</th></tr>
<tr><th>Pooled interdependence</th><th>Reciprocal interdependence</th><th>Sequential interdependence</th></tr>
<tr><td>Plumbers</td><td>Floor piping installation</td><td>90.48%</td><td>4.76%</td><td>100.00%</td></tr>
<tr><td>Masons</td><td>Floor concrete placement</td><td>3.57%</td><td>92.86%</td><td rowspan="2">100.00%</td></tr>
<tr><td>Steel fixers</td><td rowspan="2">Wall reinforcement</td><td>93.33%</td><td>6.67%</td></tr>
<tr><td>Welders</td><td>66.67%</td><td>33.33%</td><td rowspan="2">100.00%</td></tr>
<tr><td>Carpenters</td><td>Wall concrete framework</td><td>80.00%</td><td>20.00%</td></tr>
</table>

As listed in **Error! Reference source not found.**, it is obvious that the working patterns of different trades were different because of the disproportional pooled interdependence and reciprocal interdependence among group members. The main interdependence for tasks allocated by areas – piping installation, wall reinforcement and concrete framework – were pooled; while the main interdependence for tasks allocated by building components – concrete placement – were reciprocal. Therefore, it was convenient for the manager to identify the lags in working operations from such kind of visual intra-group interdependence networks. In the case, P1 and P4, as well as M3 and M7 were independent with each other, suggesting poor communication when they executed their tasks. Meanwhile P3 and P5, S0 and S4, C0, as well as C4 and C5 were reciprocally interdependent rather than pooled, implying a potential congestions or collisions within these groups. In addition, M2 and M4 were not strongly connected like other members, indicating a loose communication within the mason group. Such lags in working cooperation patterns might result in a low productivity or safety issues, the interdependence networks enabled the manager to determine the cooperation lags in a timely manner. On the other hand, the sequential interdependence measured the level of task delivery at the view of workspace usage. At any construction stage, each group was supposed to have a specific assigned task, allowing members to effectively contribute to the assignment as well as the following tasks next stage. Being aware of how many tasks were delivered for the sequential workers enabled the manager to differentiate the responsibilities from the final products. Such traceable capacity within the network was valuable to identify the root causes when construction accidents happened. For example, if the sequential interdependence were not 100%, the manager could identify isolated workers and revise the assignment allocation to make the use of workspace, thus improving the productivity.

In summary, through the above analyses, it is evident that the interdependence network is able to aid project managers to assess the performance of construction schedule and identify potential conflicts and risks in task assignments.

6. Conclusions

In order to generate a holistic view on how construction assignments are conducted on sites as well as how precise workers abide to the designed schedules, this study presents interdependence network as a novel tool to measure and visualize the task order and workforce organization based on workspace occupancies. Relying on the area-restricted nature of construction activities, the interdependence network deploys the distance of workspace distributions to identify and quantify the interdependence and then visualizes the order and organization by interlinks within or between days. Using the interdependence network, project managers can conveniently assess the appropriateness of task assignment, workspace allocation and work organization. This assessment provides a valuable tool for managers to revise the schedule and workforce organization for improving productivity and safety performances. In addition, as an objective approach to describing workforce organization, an interdependence network provides a useful representation of construction processes which can be a basis for future research endeavors [42].

However, this method still needs to be improved with further studies. For example, the scalability for larger and longer construction activities needs to be further examined, comprehensive tasks involving multiple workers to be validated, and the other measurements of interdependence to construct the networks to be implemented and compared; more available information on sites to be fused with the proposed measurement to improve the accuracy. These limitations will be focused on and tested in the future research.

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Appendix

Table I Multiple distance and similarity measurements

Name	Formula	Distance range
$D_{Euclidean}(X,Y)$	$\sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$	$[0,+\infty)$
$D_{Standardized\ Eculidean}(X,Y)$	$\sqrt{\sum_{i=1}^{n}(x_i{}^* - y_i{}^*)^2}$ $x^* = \frac{x-\mu_x}{\sigma_x}, y^* = \frac{y-\mu_y}{\sigma_y}$	[0,1]
$D_{Chebyshev}(X,Y)\ or$ $D_{Chessboard}(X,Y)$	$max(\lvert x_i - y_i \rvert)$	$[0,+\infty)$
$D_{Manhattan}(X,Y)$	$\sum_{i=1}^{n}\lvert x_i - y_i\rvert$	$[0,+\infty)$
$D_{Canberra}(X,Y)$	$\sum_{i=1}^{n}\frac{\lvert x_i - y_i\rvert}{\lvert x_i\rvert + \lvert y_i\rvert}$	$[0,n]$
$D_{Hellinger}(X,Y)$	$\frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{n}\left(\sqrt{x_i} - \sqrt{y_i}\right)^2}$	$[0,+\infty)$
$D_{Binary\ Jaccard}(X,Y)$	$\frac{\lvert X \cup Y\rvert - \lvert X \cap Y\rvert}{\lvert X \cup Y\rvert}$	[0,1]
$S_{Correlation}(X,Y)$	$\frac{\frac{1}{n}\sum_{i=1}^{n} x_i y_i - \mu_x\mu_y}{\sigma_x\sigma_y}$	[-1,+1]
$S_{Cosine}(X,Y)$	$\frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i{}^2}\sqrt{\sum_{i=1}^{n} y_i{}^2}}$	[0,1]
$S_{Jaccard}(X,Y)$	$\frac{\sum_i min(x_i, y_i)}{\sum_i max(x_i, y_i)}$	[0,1]