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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.

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.

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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 reconsider 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.

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.

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 $9\,\text{m} \times 9\,\text{m}$ grid was selected for earthmoving operations [34]; a $3\,\text{m} \times 3\,\text{m}$ for trucks [35] and $0.5\,\text{m} \times 0.5\,\text{m}$ 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