Automation in Construction 84 (2017) 335–344

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Construction safety planning: Site-specific temporal and spatial information integration

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A R T I C L E I N F O

Keywords:
Construction safety
Safety planning
Safety risk
4D BIM
Temporal and spatial information

A B S T R A C T

The Occupational Safety and Health Act was established in 1970. Since then, various injury prevention strategies have been developed and resulted in measurable improvements in construction safety management. However, the last decade has seen a deceleration in construction safety improvements, which may be due to the dynamic nature of construction jobsites. Traditional safety planning approaches rely primarily on static information, tacit knowledge, regulations, company safety policies, and 2-dimensional (2D) drawings. As a result, site-specific dynamic information, temporal (e.g. when and who will be exposed to potential hazards) and spatial (e.g. location of dangerous zones) information are currently not specifically addressed. This paper presents a formalized 4-dimensional (4D) construction safety planning process that addresses site-specific temporal and spatial safety information integration. The authors integrated safety data, which includes general safety knowledge, site-specific temporal and spatial information, from a project schedule and a 3-dimensional (3D) model. The authors conducted a case study to test and verify the proposed safety planning process. Findings show that risky activities, days, and zones can be prioritized when project schedule contains activity information regarding number of workers including occupation types and zoning plan. In addition, activity safety risk can be visualized when a 3D model is integrated. The proposed safety planning approach is expected to provide safety personnel with a proactive and site-specific safety planning tool that can be used to better manage jobsite safety. In addition, visual safety materials can enhance safety communication among project participants.

1. Introduction

The Occupational Safety and Health Act was established in 1970 and places the responsibility of construction safety on the employer. Since then, various injury prevention strategies have been developed and resulted in a measureable improvement in construction safety management [1]. However, the last decade has seen a deceleration in construction safety improvements and, in 2013, the fatality rate of the construction industry is still 2.9 times higher than other industries [2].

Safety management can be defined as a systematic and comprehensive process for managing safety risk [3]. According to British Standards Institution [3], the main components of safety management are: 1) safety policy, including safety commitment of top management, 2) safety risk management, such as hazard identification, risk analysis, and risk control, 3) safety implementation, including safety meeting/training, and 4) safety inspection. However, previous studies in the construction industry pointed out that safety programs are typically developed in an informal way [4], and safety risk analyses at construction sites are not often performed [5].

To improve safety planning, Yi and Langford [6] emphasize the importance of integration between safety management and scheduling. Hazardous situations vary during project lifetime and the schedule should be considered for safety planning [6]. However, current safety planning approaches do not consider frequent updates of a project schedule to address dynamic changes of expected hazards and safety controls. In order to create more effective site-specific safety plans, it is important to integrate safety plans and project schedules.

Another challenge of site-specific safety planning is lack of safety sources utilized. While information technology-based approaches, such as Building Information Modeling (BIM), have been widely used for project planning and progress monitoring, construction safety planning is still highly dependent on traditional sources such as 2D drawings, paper-based regulations, and tacit information [7]. As a result, current safety planning approaches limit the ability to identify and analyze hazards prior to construction and can potentially be improved by leveraging information technology.

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http://dx.doi.org/10.1016/j.autcon.2017.09.007
Received 1 August 2016; Received in revised form 3 July 2017; Accepted 12 September 2017

In order to overcome current safety planning limitations, this study proposes a formalized framework for construction safety planning through a 4D environment, which integrates 3D and time, to address site-specific temporal and spatial safety information. The proposed safety planning approach includes: (1) activity safety quantification, (2) temporal information integration (safety schedule), and (3) spatial information integration of 3D model and safety schedule (safety 4D). In addition, three main processes were tested in a case to verify the proposed safety planning approach.

2. Background research

2.1. Project schedule for construction safety

Construction projects are typically faced more uncertainties than other industries [8,9]. During the last decade, the integration of project schedules and safety plans has gained attention to identify high risk periods and minimize possible undesired events in advance [6,10,11,12,13].

Akinci et al. [10] analyzed time-space conflicts in a virtual model to detect dangerous situations by integrating a project schedule and 3D model. Wang et al. [11] and Yi and Langford [6] attempted to identify when and where risky situations would occur by combining historical accident data and project schedules. Navon and Kolton [12] utilized a project schedule in safety monitoring and control model to predict locations related to fall hazards. Hallowell et al. [13] emphasized safety risk caused by task interaction and suggested an integrated model of safety risk data into project schedules. Previous studies [6,10,11,12,13] emphasized the use of project schedules to include time information in safety planning processes. However, project schedules are frequently updated and there have been few studies addressing how safety data is dynamically updated as project schedule is updated. Therefore, this study focused on the dynamic linkage of safety risk data and schedule integration.

2.2. Information technology for construction safety

According to Esmaeili and Hallowell [14], the construction industry is saturated by safety innovations and new injury prevention practices need to be introduced to improve construction safety. Since traditional 2D drawings and paper-based sources for safety planning limit the ability to identify and analyze hazards prior to construction, information technology-based approaches, such as BIM, Geographic Information System (GIS), Virtual Reality (VR), Augmented Reality (AR), and Sensing and Warning Technologies, have been widely studied. In the architecture, engineering and construction (AEC) industry, BIM has been widely used for project planning, designing, scheduling, and estimating. Related to safety, BIM has been studied in two main aspects: 4D visualization and application of rule sets. Using 4D visualization enhances the detection of spatial conflict or congestion prior to construction [15]. In addition, 4D simulation can overcome a problem due to the conventional safety planning practice using 2D drawings and helps safety personnel detect and analyze hazards effectively [16]. A series of studies [9,17,18] developed a spatial and temporal safety/schedule integration model in a 4D environment. Their preconstruction safety planning tool considered task interaction risk factors and used user-provided semi-automated data to analyze hazardous activities in a 4D simulation. Another attempt of BIM for safety is applying safety rule checking system to automatically detect hazards and generate corresponding safety measures [19,20].

GIS for safety planning emphasizes that topography information can play an important role to prevent construction site accidents [21]. Bansal [22] integrated 4D modeling and geospatial data for construction safety in the GIS environment to predict potential hazardous places and activities.

VR has been mainly used for site safety training purposes with other visualization technologies. Hadikusumo and Rowlinson [23] developed a design-for-safety-process (DFSP) tool to identify safety hazards generated during the design phase by integrating a virtual construction environment and a safety database. The Construction Industry Institute Research Team 293 [24] introduced the System for Augmented Virtuality Environment Safety (SAVES) to educate construction workers. According the results, there was a 27% improvement in terms of hazard identification from workers trained in the VR environment.

Sensing and Warning Technologies have been applied to avoid jobsite collisions involved with heavy construction equipment, such as tower cranes or dump trucks. Choe et al. [25] evaluated the reliability of radar- and ultrasonic-based collision warning systems to minimize blind area around pickup and dump trucks. Tag-based wireless radio frequency identification (RFID) systems have been actively applied for the autonomous real-time jobsite monitoring to generate warnings on hazardous zones by detecting and tracking materials or workers on foot [26,27].

The literature shows that proactive safety mitigation practices are necessary to enhance construction site safety from project planning to construction execution phases. In addition, previous studies have indicated that information technology can overcome limitations in the traditional safety planning approach. There is little work in simultaneously leveraging modeling, scheduling and safety to enable the integration of site-specific temporal and spatial safety information.

3. Research method

Even though all safety practices are important and interrelated, this study focused on improving the safety risk analysis process which is one of the key elements in safety planning. The proposed safety risk analysis framework considers the macro level of predictable dynamic contexts of project such as activity and updates to construction documents, especially project schedules. Micro level uncertainties (e.g. equipment path, and activity delays) should be considered in the short-term based planning as well as the field of real-time jobsite monitoring and may be integrated with the macro level safety planning process. In addition, the proposed safety planning approach identified risky activities, risky work periods, and risky work zones, but specific risk controls were not provided. However, the authors expect that the proposed safety planning approach will help safety experts prepare safety controls more systematically and effectively.

Motivated by challenges and limitations of current safety planning approaches and previous research efforts to improve construction safety management using information technology, this research aims at proposing risk assessment approach to answer (1) which activities are dangerous (activity risk quantification), (2) when and where risky activities are planned (safety schedule), and (3) how risky activities can be effectively communicated (safety 4D simulation). Fig. 1 illustrates the general process of this study.

As shown in Fig. 1, an activity safety score was estimated from historical accident data using the approach described in Choe and Leite [28] and contextual information of each activity. From the integration of activity safety data and project schedule, the authors generated a safety schedule to predict risky work period. Lastly, the authors created a safety 4D simulation by linking the safety schedule and a project 3D model to analyze risky work zones. Details of each process are presented in the subsequent sections.

3.1. Activity safety score quantification

The main purpose of safety risk assessment is to estimate the safety risk of expected activities in a quantitative manner and to assist safety managers in understanding why they are dangerous prior to construction. From the quantitative safety values, risky activities can be prioritized and appropriate safety actions can be prepared when causes of risk are identified. In Choe and Leite [28], relative safety scores of 15