Fifth International Conference on Construction in the 21st Century (CITC-V)
"Collaboration and Integration in Engineering, Management and Technology"
May 20-22, 2009, Istanbul, Turkey

Modeling Three-Dimensional Space Requirements for Safe Operation of Heavy Construction Equipment

Farnaz Sadeghpour
Faculty of Engineering, Architecture and Science, Ryerson University, Toronto, Ontario, Canada, farnaz@ryerson.ca

Jochen Teizer
School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, U.S.A., teizer@gatech.edu

Abstract
The organization of space on construction sites is one of the main concerns for safety managers. Space is often limited and critical resource, since it is constrained by competing work crews, flow of materials, movement of equipment, and temporary facilities and other structures. Planning for efficient and at the same time safe site space utilization is a challenging task. This paper presents a framework for defining safe space requirements for construction activities, and will focus on heavy construction equipment. It extends previous research on determining construction activity workspace requirements by concentrating on the following three issues: (1) Identification of equipment operating space requirements and generation of equipment operating areas and volumes; (2) Measurement of spatial requirements for safe work environments; and (3) Development of an equipment selection tool based on work site constraints and safety. This paper will separate the operating space of construction equipment as a representation of a number of layers, such as equipment space, work space, rotation space, maximum reach space, and safety space. Such layers will allow to account and plan for possible interference with other objects or different layers of other resources (personnel, equipment, and materials). The presented framework is implemented using an existing database that allows the selection of equipment based on its scheduled activity in a construction project. An efficient tool for construction safety managers is presented that identifies equipment space requirements for a safe construction project and can be easily integrated with other space planning tools. Furthermore, field experiments and results using emerging real-time pro-active proximity sensing and warning technology in conjunction with work crews and heavy construction equipment is presented that helped in defining and calibrating the spatial needs and requirements of heavy construction equipment for the developed space planning tool. As a result of this work, site layout planning for safe heavy construction equipment operations becomes feasible.

Keywords
3D modeling, Heavy equipment, Resource allocation, Pro-active safety, Space layout planning

1. Introduction and Background

Construction sites are mostly dynamic environments consisting of resources such as personnel, heavy equipment, materials, and built structures that can be in relative motion to each another. If not planned properly, the sometimes unstructured or almost random movement of resources can lead to incidents between at least two objects. These incidents can then be characterized, for example, as contact collisions and are often a threat to the safety of personnel that is in too close proximity to equipment. Collisions can be attributed to various problems that begin with the closeness in which vehicles and workers (need to) operate and the space that is allocated to them.

The implementation of space allocation or planning aids in construction is important. Current safety statistics, published by the Census of Fatal Occupational Injuries (CFOI) for 2007, show high numbers of fatality rates for personnel being struck by vehicles: 21% or 1,178 of all occupational fatalities occur in the construction industry. A non-published analysis of construction related fatalities, showed that more than 610 construction workers in between the years 2004-2006 were killed in the US construction industry due to equipment related contacts. This number represents about 25% of all construction related fatalities in these three years. For the same period of time, fatalities that were caused by contacts to materials or harmful substances represented up to 24%. About 13% of all fatalities were related to specialty contractors (CFOI 2007). These numbers do not include frequent, but mostly unrecorded incidents such as near-misses (close-calls) that often are not reported to field safety managers. Subsequently, these alarming numbers show that there is a need for a warning device that alerts workers when they are in danger or are getting close to a hazardous area.

In addition, the efficient and effective resource planning of construction activities is an important attribute in construction projects, which directly affects project cost and completion time. Construction projects are typically of a complex nature where allocating traditional resources (i.e. time and money) is often interrelated with construction workspace. Space allocation is often such an important resource on construction sites, because it is often limited and shared by workers, materials, equipment, temporary facilities, and other structures. Lacking in any way of site layout planning for construction tasks can result in several problems such as blocked access to facilities, long journey paths, decreased productivity, unsafe incidents, and ultimately resulting in project delays and additional costs (Mallasi and Dawood 2002). As of today, limited attention is paid to (semi-) automated workspace planning for construction activities, including material handling requirements, equipment operation space needs, and work areas for construction crew (Chau et al. 2003). Human judgement has always been the primary solution for use of space on construction sites (Riley and Sanvido 1997) and to date there is still no conventional tool that accounts for construction site space planning. Solutions that are currently implied in practice to avoid space conflicts on construction sites include either using multi-craft crews that perform a range of activities at the same time, or allocation of a set area to one construction activity at a time. Neither solution provides optimal results as inefficiency remains.

Site logistic plans are often produced during the planning stages of a project and reach the simulation stage. However, very detailed site workspace planning is not necessarily addressed in these plans (Riley and Sanvido 1997). Many time-space conflicts result during when executing the planned tasks during the construction phase, which result in interferences of space requirements for various activities (Akinci et al. 2002). In the past decades the issue of site planning was addressed in four-dimentional (4D) and three-dimentional (3D) construction workspace planning models (e.g., Akinci et al. 2002; Chau et al. 2003; Guo 2002; Mallasi and Dawood 2002; Riley et al. 1997; Sadeghpour et al. 2006). These models aid construction managers by visualizing space usage on construction sites and detect potential spatial conflicts prior to construction. With different assumptions and approaches, these models perform time-space conflict analysis based on spatial data of the environment the task is performed in (Guo 2002). The common approach in these models is to analyze site space requirements based on the spatial needs that workers, equipment, materials, and temporary facilities operate in. Retik and Shapira (1999) and Sadeghpour et al. (2006) provide a database that allows allocating space needs for activities to construction site spatial models. However, both libraries have limited number of entries and do not provide a systematic approach for selection and identification of involved objects. Furthermore, none of the existing approaches considers safety as major criteria when allocating space to heavy construction equipment operations. In summary of existing research, construction space allocation is performed for the following four space types: 1) Materials space; 2) Equipment space; 3) Work crew space; 4)

Temporary/permanent lay down and storage spaces; 5) Moving space for resources; and 6) Temporary facility space (Mallasi and Dawood 2002).

The objective of the presented research is based on the previous knowledge on activity workspace requirements. It focuses on the following three issues in heavy construction equipment operations: (1) Identify spatial needs for using heavy construction equipment during operation; (2) Defining a safe work envelope the equipment needs to work in; (3) Introduce an equipment selection tool based on work site constraints and safety. The following sections will introduce how to select heavy construction equipment based on spatial considerations. Since heavy equipment typically is selected based on needs in productivity, availability, and size, additional focus of this research was on including safety in the decision making process when selecting the equipment type. To define the requirements that safety adds to existing spatial concepts, the safety envelope of heavy equipment was based on experimental research that determined equipment blind spots and the minimal distance resources competing for the same work space should have from each other. An equipment selection tool will be presented that includes an experimental approach for a safe work envelope.

2. Framework for Safe Space Requirements for Heavy Construction Equipment

The objective of the following sections is to define the space requirement for heavy construction equipment based on work task, schedule, cost, size, and safety. First, according to the work breakdown structure (WBS) equipment type(s) is determined to select the right equipment for a given task. Secondly, often ignored but much needed safety envelopes for equipment are experimentally found using an innovative technological approach. Lastly, both space requirements are combined and presented in a tool that allows project site and safety managers to plan accordingly in a way that is productive and cost efficient, but meets minimum safety standards.

3. Identification of Resource Types and Quantity to Complete Work Tasks

Although construction projects are known to be unique, the identification of resources and their space requirements can be planned for using the sequence and schedule construction activities have to happen to complete a project. In other words, the uniqueness of projects is mostly reflected in the construction activities that are selected. Once a project schedule is developed, work tasks are allocated resources (personnel, equipment, materials) and performed in order. Thus, the completion of construction activities becomes, to a great extent, predictable. When selecting construction equipment, space requirements are often considered on an activity level. However, assigning equipment to activities and tracking them, especially in large projects, can become cumbersome. In such projects, space allocation can be facilitated by defining and assigning spatial needs of individual equipment to its activity. For example, an excavator would be involved in tasks such as excavate, move, trench, load, and haul. Typically these tasks define the equipment type and the quantity that needs to be selected to meet the production and schedule goals. They, however, may not offer optimized solution, and in particular when considering spatial site constraints. As a result, equipment may be too large in size to work efficiently in confined spaces, may have an engine that is too small to handle the quantity in the required time, or may have large blind spots when working near many pedestrian workers and thus increase the risk of unsafe construction operations. Such considerations are necessary when planning and making equipment selection, but only become feasible once a spatial representation of equipment is fully understood.

4. Spatial Representation for Construction Equipment

Previous research work on site planning has represented equipments with rectilinear shapes. The model developed by Sadeghpour et al. (2006) allowed defining a more detailed representation for the equipment shape; however it did not consider the changes in spatial requirements during operation. Al-Hussein et al. (2001 and 2005) presented a system for selection and location of cranes on construction site based on their load capacity and detailed shapes. Hammad et al. (2005 and 2007) proposed using a combination of geometric volumes to represent a telescopic crane and its working space at different positions; i.e. crane boom at partial, intermediate, and full lifting positions. The research presented in this paper extends the previous research by analyzing a wider range of equipment types and identifying additional layers of equipment operating spaces, and in particular creating a needed safety envelope around heavy construction equipment.

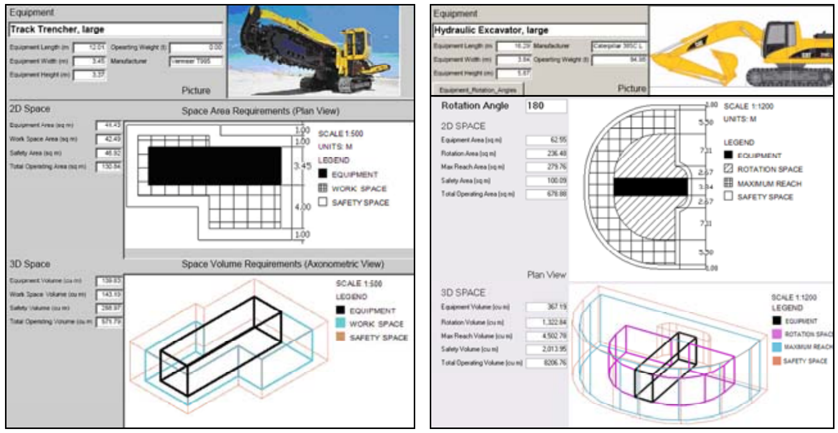

Figure 1: Space Representation for Non-Rotating and Rotating Equipment

In this research, construction equipment is divided into two categories: (1) Non-rotating equipment, which mostly maintains its shape during operation; and (2) Rotating equipment, which includes at least one rotational movement during operation. Examples for non-rotating equipment are a trench cutter or a dump truck. Examples for rotating equipment would be an articulated dump truck, an excavator, or a crane. To represent the spatial requirements the non-rotating equipment occupies during operation, ***two distinct layers*** are identified: (a) equipment space, defined by equipment length, width and height; and (b) work space, the minimal space required to operate the equipment. The only difference in occupied space between non-rotating and rotating equipment is that the work space for non-rotating equipment will not change as the equipment performs its tasks at various stages; while that of rotating equipment does due to a moving member such as a boom. Based on the type of activity and construction site conditions, moving member of rotating equipment can operate at different angles and orientations, resulting in additional occupied space that is required to operate the equipment efficiently, effectively, and safely. Consequently, as the equipment and safety spaces of rotating equipment remains the same as those for non-rotating equipment, their work space is divided into ***three additional layers*** of (c) rotation space, required to reflect rotational movement of the equipment space as defined above; and (d) maximum reach space, which extends the work space based on translational or rotational movements. All equipment requires an additional layer, the (e) safety space. A safety envelope is required to create a safe distance between other resources. All layers of equipment spaces (a-e) are preferably optimized and performed in 3D. Example of 3D spatial requirements for non-rotating and rotating equipment are shown in Figure 1.

5. Defining the Safety Space Requirements

To increase construction site safety and prevent equipment space interference, such as contact collisions, the Occupational Safety and Health Administration (OSHA) regulates to protect workers from being too close to heavy equipment. In OSHA's standards and rules it is specified, for example, that:

- All vehicles that have a blocked rear view must be equipped with a back up alarm (1926.601 (b)(4)(i)).
- Back up alarms can be by-passed by employing a signaler to warn operator and other personnel when the vehicle is backing up (1926.601 (b)(4)(ii)).
- To make ground workers more visible to operators, all workers are mandated to wear protective gear that is issued to them by their employer (1926.95 (a)).

As it can be read in these example rules, a detailed definition of how to safely operate equipment on construction sites is missing. Considering the many different cases of potential interferences that are possible between ***construction resources*** during heavy equipment operation in the construction environment,

- Worker and Equipment,
- Material and Equipment,
- Equipment and Equipment, and
- Worker, Equipment, and Material (or multiple of each at the same time)

the advantage is in representing the spatial requirements by resource type and layer. The layers of construction equipment have been previously discussed as (a) position and space occupied by the size of the equipment, (b) minimal work space the equipment operates in, (c) rotational space occupied by equipment, (d) maximum reach space resulting from rotational and/or translational movements of the equipment, and (e) safety envelope. Potential interferences between each of these layers are possible, and in regards to safety, require action (warnings or alerts to increase the situational awareness among ground workers and equipment operators).

Table 1: Typology of Spatial Interferences between Two Resources

		Resource No. 1				
		(a) Position	**(b) Work**	**(c) Rotation**	**(d) Max. Reach**	**(e) Safety**
Resource No. 2	**(a) Position**	Impossible	Alert	Alert	Alert	Warning
	(b) Work		Alert	Alert	Alert	Warning
	(c) Rotation			Alert	Alert	Warning
	(d) Max. Reach				Alert	Warning
	(e) Safety					Warning

To summarize in a matrix (see Table 1), the spatial interference of one of the above discussed scenarios is presented. As a result, spatial interference between two resources types can mean:

- Spatial allocation is ***impossible***, e.g., the physical structure of two cranes can not overlap;
- Require a ***warning signal***, e.g. interference is admissible under given circumstances (e.g. interference between safety spaces of two equipments); or
- Require an immediate ***alert***, e.g. the swing radius of two cranes dangerously interferes and requires immediate action to prevent an unsafe act.

In practice, the determination of such acceptability depends on site specifics and project conditions and it is the role of a project manager to verify and approve level of acceptability among equipment layers. This principle can be extended to analyze the possibility of overlap between different equipment spaces and other objects on construction site, such as the building under construction. When used in conjunction with space planning tools, identifying the layers and determining the interference acceptability level amongst them will assist in efficient planning for site space, as well as analyzing time-space conflicts. For example, if during examining different scenarios in space planning an overlap between space requirements of two equipments occurs, using the layers and interference acceptability described above, it can be determined whether such overlap is impossible, dangerous, or possible.

6. Measurement of Safety Space Requirements and Results

The spaces occupied by layers (a) to (d) can be directly measured using the geometry of the equipment. Layer (e), the safety envelope, can not be directly measured since it may need to be adjusted to the existing site conditions. A case study is presented that can be used as a methodology to determine a safe envelope of heavy construction equipment. Since the interaction between workers and machines currently contributes to significant number of injuries and fatalities in the construction industry, and as discussed before, the focus is on two criteria when determining safe space requirements: (1) Identifying blind spots of heavy equipment, and (2) Measuring the safety envelope using the effectiveness of so called real-time pro-active proximity warning and alert devices to detect and avoid space interferences of resources.

6.1 Identification of Blind Spots

The blind spots of common construction equipment including, but not limited to, excavators, rollers, dozers, dump-trucks, and cranes, may be determined through the use of 3D laser scanning equipment. A complete 360-degree laser scan of each piece of equipment was collected, and each completed scan will yield a virtual model. Since it is common on construction sites for equipment to be altered by the contractor, owner, or equipment operator to their needs, the scans taken are of equipment as they are in the construction field. For that reason, the laser scanner was needed to gain a pictorial representation of the equipment as it is used in the construction industry in real situations. These 3D models will aid in determining all blind spots (direct and indirect) of the equipment in different types of scenarios and poses, including operator height differences. Direct line-of-site is what the operator can see in front of him/her without the use of cameras or mirrors. When direct line-of-site is blocked it is termed a direct blind spot. An indirect blind spot is an area of visibility that is obstructed even with the use of cameras or mirrors. Once these blind spots have been determined, the necessary safety zone can be established for each piece of equipment. The safety zone is the area in which an alarm sounds, alerting both the operator(s) and worker(s) that the safety zone is breached, and a collision is probable (Fosbroke 2004).

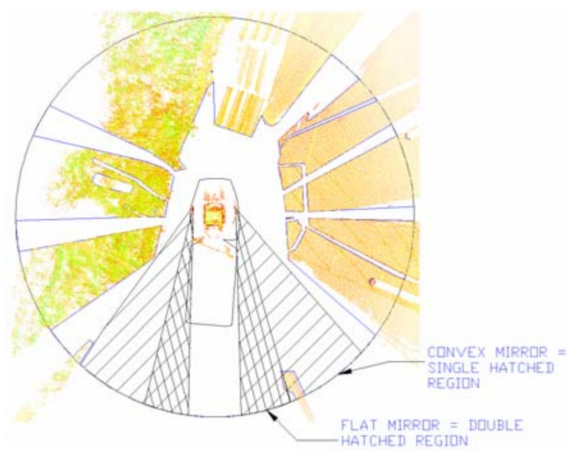

Figure 2: Laser Scan data of blind spots with visible regions from mirrors at 15m.

Figure 2 shows the blind spots of the off-highway dump truck in plan view within a 15 m radius around the equipment. Figure 2 also shows the regions visible by the mirrors, indicated by the hatched areas. The effect of "articulation" about a pivot point may cause reduction of possible visible regions by mirrors in heavy equipment. The dump truck is in fact an articulating dump truck, in which the pivot point behind the cab of the equipment, when the vehicle is turning, will most likely inhibit the view visible to the operator in the mirror(s). In this case, convex mirrors may assist the operator. The blind spots of the off-highway truck were determined for actual site conditions during the scan. The process to determine the blind spots of equipment are as follows:

1. Laser Scan Inside of Equipment Operator's Cabin Inside and Outside
2. Measure Cabin geometry and Field-of-View (FOV)
3. Identify Indirect and Direct Blind Spots
4. Develop Final Blind Spot Diagram

Table 2 displays the results for four pieces of equipment. The table shows the direct blind spots in the first three columns; displaying the FOV for front, side, and plan views. The next columns show the increase in FOV and decrease of blind spots when the mirrors are used, this value is a negative value. The final column displays the net value of blind spots when combining the direct blind spots and the subsequent aid that mirrors bring. The dump truck uses convex mirrors in addition to flat mirrors while the roller uses only flat mirrors.

Table 2: Equipment Operator's Visibility by Equipment Type (in %)

Equipment Type	Unobstructed/Visible Areas Without Mirrors			Improved View With Different Mirror Types in Plan View			Net for Plan View
	Plan	Front	Side	Flat	Convex	Overall	
Dump Truck	49.9	86.7	72.8	-7.8	-12.6	-20.4	29.5
Roller	27.9	62.5	71.7	-4.4	N/A	-4.4	23.5
Motor Grader	51.4	67.1	71.0	N/A	-7.0	-7.0	44.5
Excavator	52.0	65.6	75.0	-2.1	-0.7	-2.8	49.5

The resulting safety envelope required for each piece of equipment is unmeasured, and with many variables like equipment speed, human workers, etc. there are many unknowns would need to be measured before any accurate safety zone may be calculated. However, these initial blind spot results show that they are large, and any safe space requirement for heavy construction equipment may reach far beyond the maximum reach distance as defined previously.

6.2 Measuring Safety Envelope

From the background information and blind spot measurements the safety envelope of heavy construction was determined using a proximity detection and alert device. As details to the proximity detection and alert device are explained in Teizer (2007 and 2009), this section focuses briefly on its results. In field trials heavy construction equipment and ground workers were each given proximity sensing devices. Given that they are in close and pre-defined distance to each other, both devices issue a warning and alerting signal. A primarily focus of these experiments to determine a realistic distance close to articulated dump trucks, as seen in Figure 3. Entering the safety envelope immediately activated both the ground worker's and equipment operator's warning and alert device. The minimal safe distance when the alerts activated was about 20 meters. As mentioned previously, setting the alert distance depends on existing site conditions. As a result, as the terms defined in this paper, the following formula can be used for measuring the space requirements (safety envelope) for safe heavy construction equipment operation:

Safety Envelope = Space {Equipment position, Work Task, Rotation, Maximum Reach, Safety}

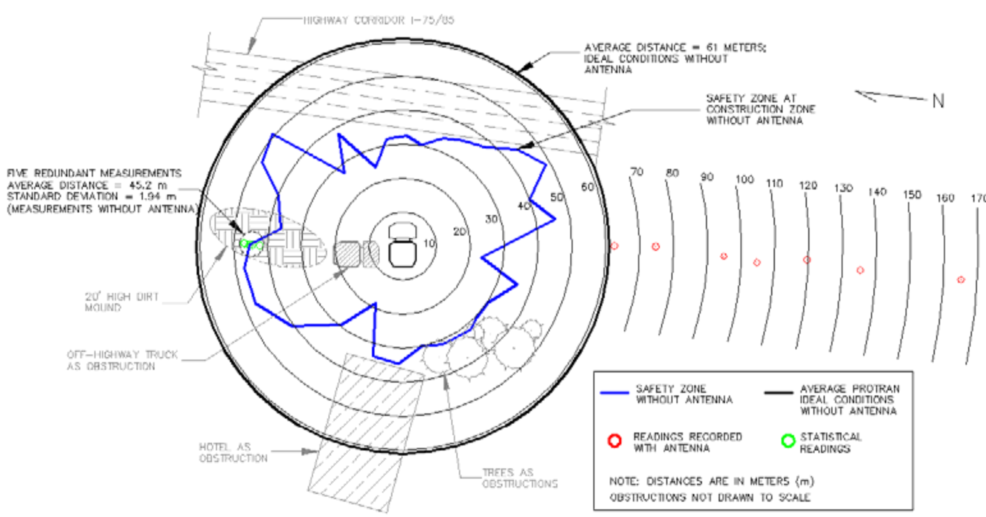

Figure 3: Space Requirement (Safety Envelope) for Safe Equipment Operation

7. Conclusion

This paper has identified that space is limited and critical resource in construction. When it comes to heavy equipment operation in the construction industry, planning for efficient and safe site space utilization is a challenging task. This paper presented a framework for defining safe space requirements when using equipment based on geometry and a safety envelope. Latter one was derived from field measurements of blind spots using laser scanning and real-time proximity and alert devices. A formula resulted was developed that allows to determine the space requirements for safe heavy construction equipment operations. Since current safety practices are not sufficient in preventing worker injuries and fatalities when being too close to heavy equipment, this study will help guide practitioners in more efficiently, effectively, and safely allocating space to equipment operations in the construction field.

8. References

Akinci, B., Fischen, M., Kunz, J. (2002). “Automated Generation of Work Spaces Required by Construction Activities.” J. Constr. Engng. Mngm., 128(4), 306-315.

Al-Hussein, M., Alkass, S., and Moselhi, O. (2001). “An Algorithm for Mobile Crane Selection and Location on Construction Sites.” Constr. Innov. J., 1(2), 92-105.

Al-Hussein, M., Alkass, S., and Moselhi, O. (2005). “Optimization Algorithm for Selection and On Site Location of Mobile Cranes.” J. Constr. Engng. Mngm., 131(5), 579-590.

Chau, K.W., Anson, M., and Zhang, J.P. (2003). “Implementation of Visualization as Planning and Scheduling Tool in Construction.” Build. & Envrn., 38(5), 713-719.

CFOI (2007). Fatal Occupational Injuries By Event Or Exposure, 2001-2006. (2007). Census of Fatal Occupational Injuries. U.S. Bureau of Labor Statistics <http://www.bls.gov/news.release/cfoi.toc.htm> (Accessed July 12)

Fosbroke, D.E. (2004). “NIOSH Reports! Studies on Heavy Equipment Blind Spots and Internal Traffic Control”. Roadway Work Zone Safety & Health Conference, Baltimore, MD. (http://www.workzonesafety.org/files/documents/news_events/wz_conference_2004/heavy_equipment.pdf, Accessed May 12, 2008)

Guo, S. (2002). “Identification and Resolution of Work Space Conflicts in Building Construction.” J. Constr. Engng. Mngm., 128(4), 287-295.

Hammad, A., Zayed, T. M., Zhang, C., and Wainer, G. (2005). “Representation and Analysis of Spatial Resources in Construction Simulation.” Proc., 2005 Winter Simulation Conference, Orlando, FL, USA,1541-1548.

Hammad, A., Zhang C., Al-Hussein, M., and Cardinal, G. (2007). “Equipment Workspace Analysis in Infrastructure Projects.” Can. J. Civ. Eng., 34(10), 1247-1256.

Mallasi, Z., and Dawood, N.N. (2002). “Registering Space Requirements of Construction Operations Using Site-PECASO Model.” Proc., Distributing Knowledge in Building, CIB W78: Int. Council Res. & Innov. Build. & Constr., Aarhus, Denmark, 1-8.

Retik, A., and Shapira, A. (1999). “VR-based planning of construction site activities.” J. Automat. Constr., 8(6), 671-680.

Riley, D. R., and Sanvido, V. E. (1997). “Space Planning Method for Multistory Building Construction.” J. Constr. Engng. Mngm., 123(2), 171-180.

Sadeghpour, F., Moselhi, O., Alkass, S. T. (2006). “Computer-Aided Site Layout Planning.” J. Constr. Engng. Mngm., 132(2), 143-151.

Tommelein, I. D., and Zouein, P. P. (1993). “Interactive Dynamic Layout Planning.” J. Constr. Engng. Mngm., 119(2), 266-287.

Teizer, J., Lao, D., and Sofer, M. (2007). “Rapid Automated Monitoring of Construction Site Activities using Ultra-Wideband”, Proc. 24th Int. Symposium on Automation and Robotics in Construction, Kochi, India, 2007, pp. 23-28.

Teizer, J., Fullerton, C.E., and Allread, B.S. (2009). “Pro-Active Real-Time Proximity Warning System for Workforce Safety in Earthmoving Operations.” J. Const. Engng. Mngm. (under review).