Spatial and Temporal Exposure to Safety Hazards in Construction

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Abstract: Given the dynamic nature of construction sites, analysis of construction activities and their related hazards is inadequate for reliable risk assessment if it does not explicitly account for the likelihood of exposure of potential victims to hazardous situations. In traditional risk level calculations for manufacturing industries, the number of victims is factored with the likelihood of an accident and the potential severity, but the victims are simply assumed to be those typically present at the accident location. In construction, exposure cannot be accounted for at a generic metaproject level: it must be assessed at the level of the activities and the physical context in which they are performed. Conceptually, accidents are "loss-of-control events" to which victims are exposed; without exposure, no accident is assumed to occur. A set of algorithms has been developed to demonstrate estimation of the likelihood of exposure of construction workers to loss-of-control events. The algorithms have been implemented in a prototype software application designed to predict fluctuating risk levels in construction projects. The software implements the "construction hazard assessment with spatial and temporal exposure" model for managing safety in construction, which empowers planners at all levels to adjust construction plans to mitigate high levels of risk or to undertake appropriate proactive measures to ensure safety when high risk levels are unavoidable.

DOI: 10.1061/(ASCE)0733-9364(2009)135:8(726)

CE Database subject headings: Algorithms; Construction management; Lean construction; Occupational safety; Spatial analysis; Time dependence.

Introduction

Construction is one of the most dangerous industries worldwide. It is a leading contributor of work related fatalities (Ahmed et al. 2000; Findley et al. 2004; Gyi et al. 1999). The International Labor Organization (ILO 2003) reports conservative estimates that at least 60,000 people are killed on building sites annually worldwide. Many hundreds of thousands more suffer serious injuries and ill health. The main causes of injury include falling, being crushed, being struck by falling objects or equipment, and electrocution. Table 1 indicates the fatality rates (fatalities per 100,000 employees) in the United States, the European Union, and Israel during the 1990s. The fatality rate in construction is significantly greater than that of industry in general.

Accidents are not random events. Research has indicated that human errors are involved in some two-thirds of all fatal work related accidents (Feyer and Williamson 2006). While human factors play a significant part in accident causation, it is difficult to establish statistical relationships for general cases for use in predicting levels of danger. Task analysis can aid safety management (Kirwan and Ainsworth 1992) because human factors affecting standard operating procedures, training, and work environments can be considered, rather than focusing only on skill, rule, or knowledge based human errors that are among the immediate causes of accidents. Proactive preliminary hazard analysis (sometimes referred to as job safety analysis—JSA), performed repeatedly prior to performance of any task, is considered to be an effective and essential industrial safety measure (Brown 1976; Goetsch 1996; Holt 2001).

Construction, however, presents significant obstacles to repeated JSAs. Construction sites undergo dynamic change in ways that fixed industrial facilities do not: work teams are transient, the physical structure and spaces change constantly, and sites are exposed to the environment and changes in weather. Another difference is that in construction, workers of one team are frequently exposed to dangers posed by the workers of other, unrelated teams. Performing risk analysis before any activity at any time is essential but difficult, even if the same activity is performed repetitively, since site conditions change through time. This demands more effort than most contractors or workers are willing to invest, and therefore, safety management in construction sites commonly suffers from low levels of efficiency, with effective risk analyses performed rarely (Tang et al. 1997). In the absence of an efficient and effective way of predicting peak risk levels, safety management at construction sites is performed at constant levels of effort, focusing on provision and use of personal safety equipment, training, accident and near-miss investigations, and taking steps to fulfill regulatory requirements.

To allocate safety management resources effectively, and to enable safety-conscious planning of work to be performed on site, a method is needed that can augment standard "static" JSAs by enabling automatic prediction and calculation of the probabilities

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Note. This manuscript was submitted on November 27, 2007; approved on February 13, 2009; published online on July 15, 2009. Discussion period open until January 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 135, No. 8, August 1, 2009. ©ASCE, ISSN 0733-9364/2009/8-726–736/$25.00.

Table 1. Fatality Rates in Construction and in Other Industries for the United States, European Union, and Israel

Region	Construction fatality rate (1990–2000)	General industry fatality rate (1990–2000)	Four most frequent fatal accident types	Reference
United States	18–19	4–5	Falls (36%)	(Kartam and Bouz 1998)
			Struck by vehicle (24%)	(Huang and Hinze 2003; OSHA 2002)
			Caught in/between (12%)	
			Electrocution (13%)	
European Union	13–14	3–4	Falls	(Dupre 2001)
			Struck by vehicle	
			Struck by falling objects, materials, or tools	
			Electrocution	
Israel	20–21	2–3	Falls (36%)	(CBS 2005; MITL 2007)
			Caught in/between (12%)	
			Electrocution (6%)	
			Collapse (4%)	

of workers becoming exposed to loss-of-control events that may occur due to human error or equipment failure at any time. Ideally, planners could evaluate expected risk levels for each upcoming planning window for each work crew and then either reschedule work to avoid particular peaks of risk level or, if they are unavoidable, plan for appropriate safety measures to be taken (Rosenfeld et al. 2006). This can be done when preparing a master construction schedule, when preparing medium-term look-ahead plans, or in weekly work planning. Saurin et al. (2004) proposed that safety concerns be incorporated directly into the Last Planner system (Ballard 2000), with explicit evaluation of the number of safe work packages.

Although assessment of risks is crucial for improving safety management, precise evaluation is not a necessary or appropriate goal (Jannadi and Almishari 2003); an estimated predicted level of risk would suffice. For lack of any practical method for actually calculating fluctuating risk levels, construction planners typically rely on professional and personal experience and group assessments (ISI 2000; Lingard and Holmes 2001; Manuele 2005).

The methods and models available assess the risks that crews' own activities pose to themselves (Jannadi and Almishari 2003; Tam et al. 2004). While this is sufficient for most industrial applications, construction crews not only endanger themselves but also they are commonly exposed to risks that derive from the activities of other crews' activities in other places on site. For example, a crew fixing stone cladding on a façade poses a significant danger to any workers occupied in activities below them, such as installing drains on the ground floor. The crews are technically independent of one another and do not occupy the same space, and so might be scheduled to work simultaneously. For accident risk level assessments to be of practical use, a risk assessment model cannot ignore risks of this nature (Mitropoulos et al. 2005).

To make such assessments, information from multiple sources must be retrieved, integrated, and evaluated: the physical form of the building as it will be at each stage of construction, the geometry and location of a wide variety of temporary structures and moving equipment, the expected locations and activities of all the people present on site, the nature and inherent dangers of the production activities, various environmental, organizational, and human factors that influence behavior, etc.

The "construction hazard assessment with spatial and temporal exposure" (CHASTE) method (Rozenfeld 2008) was specifically developed to provide such predictive capability. For any given project, a set of possible loss-of-control scenarios is generated from a digital construction plan using a construction job safety analysis (CJSA) database (Rozenfeld 2008). A safety risk level can then be generated for every possible case of exposure to a loss-of-control event (Mitropoulos et al. 2005). The results can be accumulated and reported at different levels of resolution: over different periods of time, for different workers or crews, and for different expected accident scenarios and severity levels.

A software application developed in-house for Bechtel (Berg 2006), which generates reports of risk levels through time, underscores the need for sophisticated prediction of safety risks in construction. In that system, attributes that define danger levels according to a predetermined unitless scale are assigned to each major construction activity. The activities are associated with groups of building objects in a building information modeling (BIM) model. Construction planners can then view the four-dimensional computer-aided design (4D CAD) model (McKinney and Fischer 1998) of the project with the building's components displayed in colors that indicate the risk level associated with their construction, which changes over time. However, this system does not calculate the risk levels; it simply enables clear and powerful visualization of risk levels assessed directly by the construction managers responsible for the project.

The goals of this research were to define, develop, and test algorithms for computing the probability of potential victims to be exposed to a set of loss-of-control scenarios as part of the synthesis and development of the CHASTE method. After a brief overview of the method, the next sections define the context for the algorithms. Two numerical examples are provided. The algorithms are essential for the overall CHASTE approach, which relies on the identification of exposure of workers to hazards. It is this functionality that enables the evaluation of the impact on risk levels that can be achieved through adjustment of construction schedules at all degrees of resolution. Implementing the CHASTE method in construction planning software could greatly enhance the ability of planners to schedule work safely in two ways: by risk leveling and short-term pull scheduling of safety management activities. Its use in practice would thus play a role in reducing the number of injuries and deaths on construction sites.

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Table 2. Examples of Loss-of-Control Events and Exposures

ID	Construction activity (source)	Source activity location	Loss-of-control event	Victim	Victim's activity	Victim's location	Potential accident type
A	Stone tile facing	Façade	Drop stone tile	Plumbing laborer	Laying pipe	On ground beside scaffold	Struck by falling object
B	Place concrete	Floor slab	Neglect to install railing	Engineer	Surveyor	On floor slab	Fall from height
C	Erecting HVAC duct	Interior floor	Hand slips while operating power tool	MEP laborer	Erecting HVAC duct	Same as source location	Injured by tool
D	Installing steel balustrades	Stairwell	Welding ignites fire	Painter	Painting	One floor above	Burns
				Carpenter	Installing cabinets	Two floors above	Smoke inhalation

Overview of the CHASTE Method

Eq. (1) summarizes the main assumptions of the CHASTE method

$$\mathrm{RL}_{ij[T_1:T_2]} = (E_{S_{ij}} \times E_{T_{ij}} \times F_E \times n_i \times n_j) \times (P_{ij} \times F_P) \times S_i \tag{1}$$

where $\mathrm{RL}_{ij[T_1:T_2]}$ = safety risk level that is predicted for a crew of workers, j, exposed to a loss-of-control event caused by a crew i in any discrete time interval from T_1 to T_2. The right hand side of the equation has four parts.

- $E_{S_{ij}} \times E_{T_{ij}} \times F_E$—Calculation of the exposure in time and space. $E_{S_{ij}}$ and $E_{T_{ij}}$ are the probabilities of exposure in space and time, respectively, and are calculated according to the algorithms presented in this paper. F_E accumulates intensifying or mitigating factors affecting the likelihood of exposure that are dependent on the local and temporal conditions that exist at any particular construction site. These include human factors (personal level of risk aversion, personal discipline, and understanding of primary site language) and managerial factors (degree of safety instruction provided to workers who may be exposed, safety management policy, schedule pressure).
- $P_{ij} \times F_P$—An estimate of the probability per worker in crew i of a loss-of-control event occurring based on a probability P_{ij} and intensifying factors, F_P, which are dependent on the local managerial context and physical environment. A loss-of-control event is an unwanted, unintended event in which control over a hazard is lost, such as dropping a hammer; it may or may not result in an accident. The probabilities for sets of loss-of-control events are established using the CJSA approach (Rozenfeld et al., unpublished data, 2007), which consists of structured interviews of a large sample of experienced construction personnel. The advantage of assessing loss-of-control events as opposed to accidents is that they are orders of magnitude more frequent and, therefore, much easier to assess. Examples of intensifying factors are congestion of workers in an area, impaired visibility due to dust or smoke, climate factors such as heat, cold, or precipitation, etc.
- S_i—The expected severity of the result of potential accident scenarios arising out of a loss-of-control event originating from crew i. This value is computed according to severity "weights" that must be provided by the users to reflect their relative and subjective sensitivities to different levels of injury or damage.
- n_i and n_j—The numbers of workers in each of crews i and j.

Once the risk level has been computed for all the accident scenarios that were generated, the results can be summed and reported in a variety of ways. Expected fluctuations in risk level can be reported along a time axis for workers or crews, for locations in a building, for construction activity types, for accident result types, or for any combination of these parameters.

Exposure to "Loss-of-Control" Events

A central concept in the CHASTE method is that for a construction accident to occur, the victim or victims must be exposed to a loss-of-control event that can be associated with a construction activity. A *loss-of-control event* is defined as an event in which control over a hazard is lost. A *hazard* is an inherent characteristic or capability that holds the potential to cause harm to a person or process. Hazards are distinct from risks: a hazard relates to the potential for harm, while risk is a measure of the likelihood that harm may be caused under certain conditions and relates to the degree of severity expected (Holt 2001). *Exposure* is defined at two levels: *regional exposure* and *direct exposure*. Regional exposure exists if there is any possibility that a potential victim will be present in a region that is exposed to an incident resulting from a loss-of-control event, while direct exposure exists if the potential victim is directly in the path of harm. A person may be present in an exposed region, but remain unharmed when a loss-of-control event occurs by virtue of not being directly exposed. The CHASTE method can only calculate the regional exposure; all subsequent references to exposure in this paper should be understood to refer to the regional exposure. Table 2 provides numerous examples of loss-of-control events and illustrates different ways in which loss-of-control events and exposure can be classified. Case A is a straightforward example where the source of the danger and the victim exposed to it are distinct from one another and the accident occurs immediately following the loss-of-control event. Case B differs from Case A in that the victim is exposed in time to the loss-of-control event from its first occurrence until the situation is rectified, which may be some time after the source activity has ended. Case C describes a situation in which the worker in the source activity is exposed to his or her own loss-of-control event. Case D shows that multiple potential victims may be exposed to a loss-of-control event and that an event may result in more than one type of accident. Note also that the definition does not imply that the loss-of-control event is the sole cause of the accident, but rather that it is a necessary condition for an accident to occur.

It should be emphasized that the algorithms for the CHASTE method presented here do not calculate the probability of an accident actually occurring, but rather the probability that a potential victim will be exposed to a loss-of-control scenario that could possibly lead to an accident (Rozenfeld et al., unpublished data,

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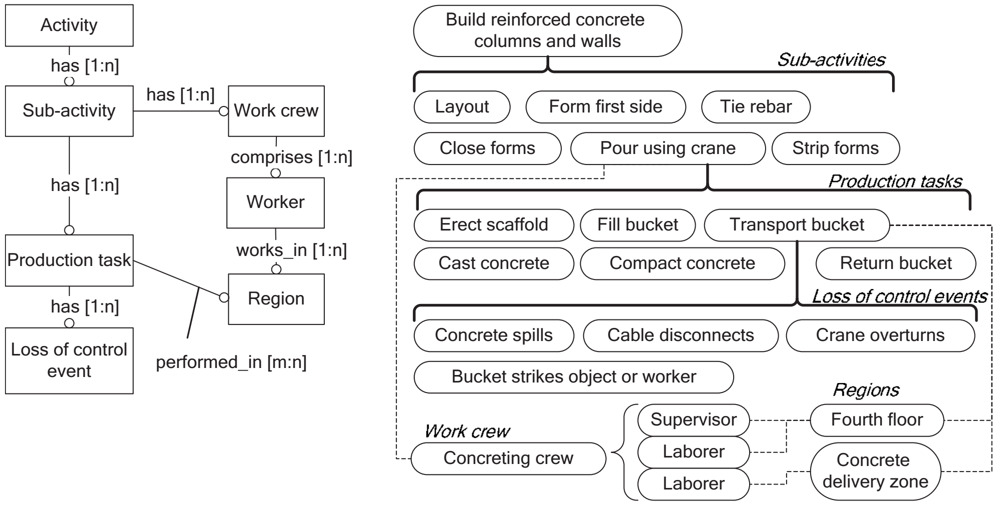

Fig. 1. Data structure of the CJSA knowledge base in Express-G (at the left) with an example

2007). This is an important distinction which follows from the distinct definitions of regional and direct exposures stated earlier. For example, in Case B of Table 2, any person present on the floor slab between the time when the concrete is placed and a barrier to falling of some kind is installed, is exposed to the danger of falling. The loss of control is the act of negligence in leaving the edge of the slab unprotected, and the probability of exposure for the engineer to the risk of falling will be a function of the amount of time spent on the slab, the likelihood of his or her presence in proximity to the unprotected edge during the time spent on the slab, and the initial probability of the loss-of-control event occurring. In this sense, the risk level calculated by the CHASTE method does not imply that an accident is likely to occur, only that it can. An additional multiplier—a measure of the probability of the engineer actually falling when exposed to an unprotected edge—would be needed to calculate the probability of the accident. That probability is beyond the scope of this paper, as is the likely degree of severity of any accident that may occur.

Input Information

The data needed for calculating exposure probabilities in any project are the construction plan and the building geometry. The construction plan defines the activities to be performed, the primary location region for each activity, and the resources that will be employed. Construction plans, whether prepared using critical path method software tools or more sophisticated line-of-balance tools (Seppanen and Aalto 2005), do not define activities at the level of detail resolution required for calculating exposure; information is needed on the probable locations of workers at any given time. The gap is bridged by detailing the high-level activities into subactivities and detailed tasks using the CJSA knowledge base (Rozenfeld et al., unpublished data, 2007). The data structure of the knowledge base is depicted in Fig. 1. The activities in a project schedule correspond to the activities in the knowledge base, which are detailed into subactivities and then further into production tasks. The likely locations of workers are defined for the production tasks; they may be at the primary location defined for the activity or at other secondary locations, with different total expected durations at each. Possible loss-of-control events are also detailed for each production task.

The building's spatial geometry is defined as a collection of bounded surface regions, representing the spaces in which work is performed, each with an identifying name and an elevation. This information can be extracted simply from a subset of the information that would normally reside in a model defined using a BIM tool (Eastman et al. 2008), but it can also be generated from two-dimensional drawings where a BIM model is unavailable. The building geometry must show temporary structures, such as scaffolding; this is done in a fashion similar to that employed by Akinci et al. (2002) for analyzing spatial interference in construction. Fig. 2 shows the working spaces for a small eight story building. Note the horizontal and parallel strips that represent scaffolding workspace on the north and south façades of the building.

Temporal Exposure

Exposure in time occurs when a potential victim is present in a region that may be affected by a loss-of-control event that may occur concurrently with their presence in the exposed region. Workers' locations are associated with distinct process tasks, which are detailed for each subactivity in the CJSA knowledge base. The equation for calculating exposure in time of workers performing task m of some subactivity i, to the loss-of-control events generated in task n of some other (or the same) subactivity j, is as follows:

$$E_{T_{ij}} = 0 | t \leq \max(S_i, S_j)$$

$$E_{T_{ij}} = SD_i \times SD_j | \max(S_i, S_j) < t \leq \min(F_i, F_j)$$

$$E_{T_{ij}} = 0 | t > \min(F_i, F_j)$$

where $E_{T_{ij}}$ = probability of exposure in time; S_i and S_j = planned start times of the two subactivities considered; F_i and F_j = planned finish times; and SD_m and SD_n = proportional times spent on each of the two work tasks being compared expressed as a percentage of the total duration of the subactivities of which they are each a part.

Fig. 3 shows an example of how temporal exposure is calculated. Two subactivities, 1 and 2, overlap in time for the duration

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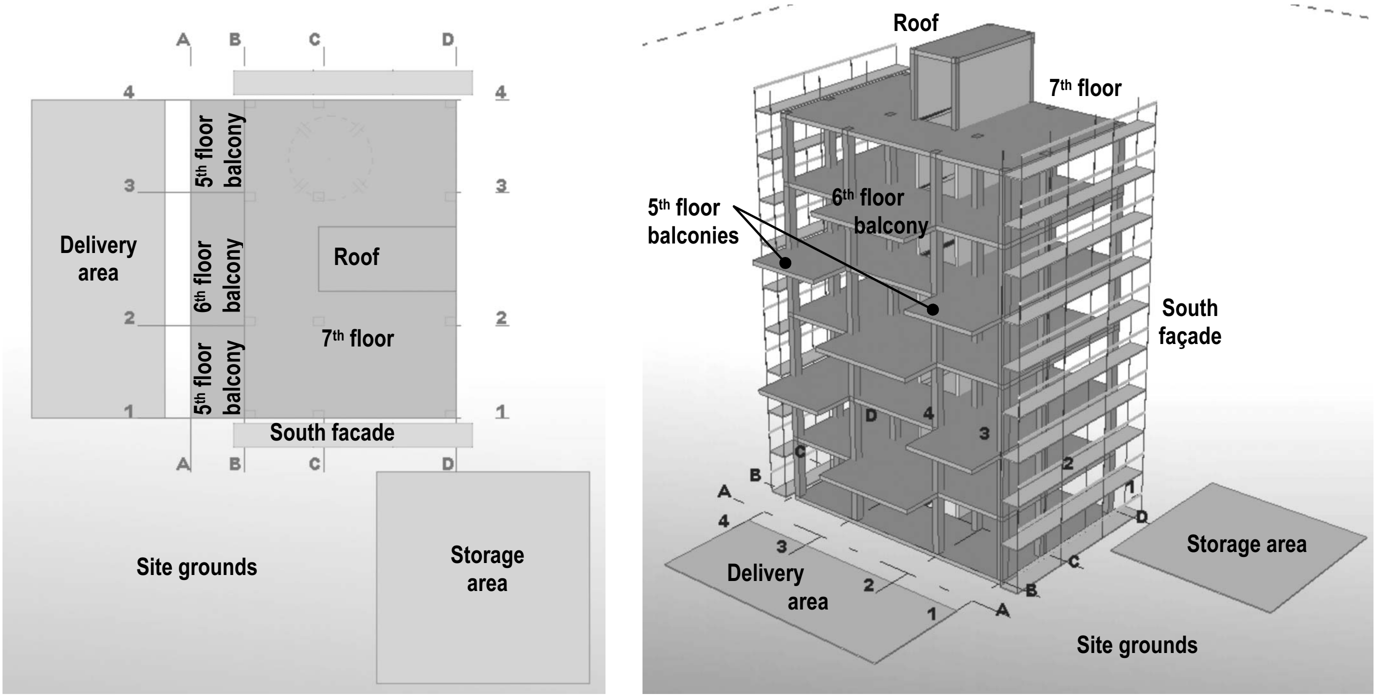

Fig. 2. Geometric definition of a building's space

from Day 7 to Day 9. The source task is executed on average for 30% of the time of Subactivity 1, while the target task is performed for 40% on average of Subactivity 2. The probability of exposure of workers performing the target task to the loss-of-control event occurring in the source task is therefore 30% $\times 40\% = 0.12$ over the period from Day 7 to Day 9, and zero for the rest of the duration of Subactivity 2.

A special case occurs when a worker or crew endanger themselves directly, where both $m=n$ and $i=j$. In this case, $E_{Tij} = SD_m|S_i < t \leq F_i$, i.e., for the full duration of the subactivity.

Spatial Exposure Algorithms

Exposure in space, of a potential victim to a potential accident that could arise from a loss-of-control event, is considered to occur when the space that may be impacted by the loss-of-control event overlaps with the space in which the victim is present. Conceptually, the overlap can be represented, as shown in Fig. 4.

Different algorithms are needed for different types of loss-of-control events because the nature of the overlap between spaces varies: vertical overlap is required for events related to falling objects, while horizontal overlap is relevant for fire, smoke, and gas related incidents. All of the algorithms are founded on the same assumptions:

- That the probability of a potential victim being present at any given location within the extents of the region he or she is present in (labeled R_j in Fig. 4) is assumed to be uniform throughout that space.
- That the probability of a loss-of-control event impacting on any given location within the extents of the possible impact region (labeled R_i in Fig. 4 and derived from the space in which its source task is performed in accordance with the type of loss-of-control event considered) is also uniform throughout that space.

These assumptions allow the probability of exposure to be computed using the proportions of the spaces, as stated in Eq. (2):

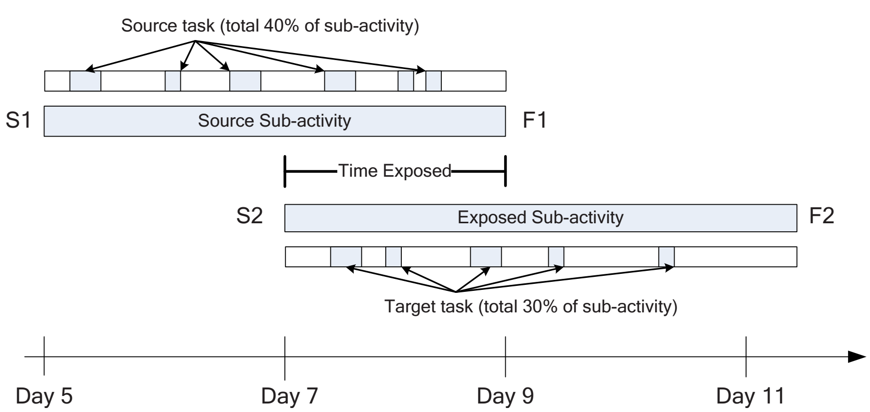

Fig. 3. Resolution of exposure in time

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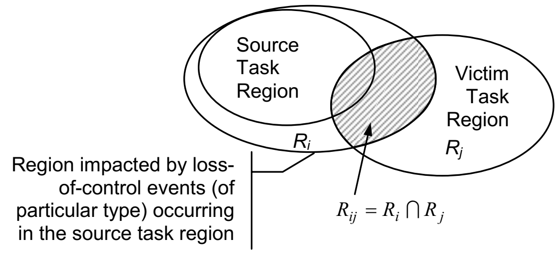

Fig. 4. Conceptual view of exposure in space

$$E_{S_{ij}} = \frac{A_{ij}}{A_i} \times \frac{A_{ij}}{A_j} = \frac{A_{ij}^2}{A_i A_j} \qquad (2)$$

where $E_{S_{ij}}$ = probability of exposure in space; A_i and A_j = areas of the source impacted region and the victim's task region, respectively (regions R_i and R_j); region $R_{ij}=R_i \cap R_j$; and A_{ij} =area(R_{ij}).

A special condition occurs for most types of loss-of-control event, where workers or crews are exposed to events that arise from their own activity. As expected, the probability of exposure $E_{S_{ij}}=1$ because $A_{ij}=A_i \equiv A_j$. Although Eq. (2) holds for the general case, the ways in which the spaces to be compared are generated differ significantly according to the type of loss-of-control event being considered. The algorithms for three of the main types of loss-of-control event are detailed in the following subsections.

Falling Objects

"Falling objects" is a class of loss-of-control events that commonly result in tools or materials falling. Examples are a worker dropping a hand tool or a brick, a stone cladding piece being dislodged from a palette on a scaffold, etc. Two possibilities are considered: (a) objects falling within a work location a short height to a surface on which the task is being performed and (b) objects falling outside of the work location to a surface below the work area. For the first, Eq. (2) is valid as is. For the second, the algorithm is as follows (with reference to Fig. 5).

Step 1. Offset the perimeter of the source work area, region R_i, in which a loss-of-control event is assumed to occur, outward to a distance of wf_2, generating region Rf_i. wf_2 is a parameter that defines a likely maximum distance that an object would be expected to fall from the edge when dropped. Note that region Rf_i extends around the full perimeter of R_i including the area of region R_{ij} in Fig. 5.

Step 2. Generate region R_{ij}, which is the region of exposure for workers present in region R_j, by calculating the Boolean intersection between region Rf_i and region R_j.

Step 3. Calculate the approximate area of region Rw_i using the equation $Aw_i = wf_1 / wf_2$, where A_{ij} = area of region R_{ij}. wf_1 defines how close a worker must be to the edge of the region in order for an object to fall over the edge.

Step 4. Calculate $E_{S_{ij}}$, which is the probability of a worker in region R_j being present in the region R_{ij} simultaneously with a loss-of-control event occurring in region Rw_i due to the presence of a worker in region R_i, using Eq. (3)

$$E_{S_{ij}} = \frac{Aw_i}{A_i} \times \frac{A_{ij}}{A_j} \qquad (3)$$

where Aw_i = area of region Rw_i; A_{ij} = area of region R_{ij}, etc.

Objects Falling from a Crane

This type of loss-of-control event, like others that involve transport of materials from place to place, is more complex than the case of falling objects dropped by workers because there are three distinct source locations for R_i—the loading location (region R_L), the transport path (region R_P), and the delivery location (region R_D), as in Fig. 6. The spatial exposure of a worker in any target region, R_j, is computed separately for each of the three source regions. The algorithm is as follows.

Step 1: Calculate the exposure in the loading location. Set R_L as R_i and calculate $E_{Lj}=E_{S_{ij}}$ using Eq. (2).

Step 2: Calculate the exposure in the path location. Generate region R_P, which is the region of the path between the loading and delivery regions. Based on the paths recorded using automated monitoring of cranes for a range of activity types in earlier research (Sacks et al. 2005), the path region is approximated, as shown in Fig. 6. The shape is derived by generating two circles, circumscribed around the loading and delivery regions respectively, joining the circles with lines tangential to each, Boolean subtraction of the loading and delivery zones from the resulting region, and, finally, Boolean intersection of that region with the circle describing the cranes operating area. The exposure for the path region is then calculated by setting R_P as R_i and calculating $E_{Pj}=E_{S_{ij}}$ using Eq. (2).

Step 3: Calculate the exposure in the delivery location. Set R_D as R_i and calculate $E_{Dj}=E_{S_{ij}}$ using Eq. (2). An additional step is required because the crane load cannot be present in all three regions simultaneously. At any point in time, it can only be above one of these mutually exclusive regions. Each of E_{Lj}, E_{Pj}, and E_{Dj} is multiplied by a factor that represents the proportion of the total

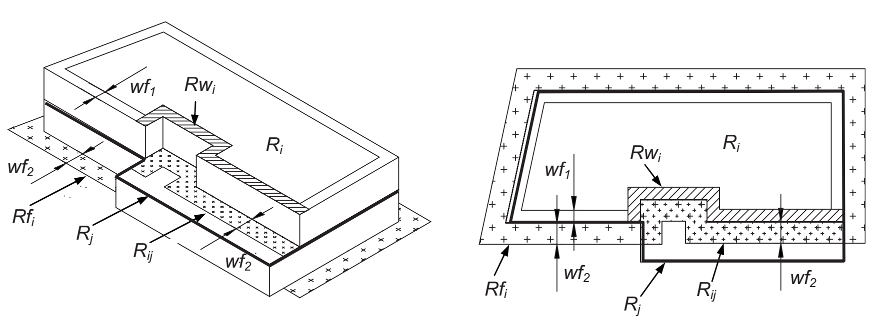

Fig. 5. Generation of areas for the calculation of spatial exposure probability for objects falling outside a floor

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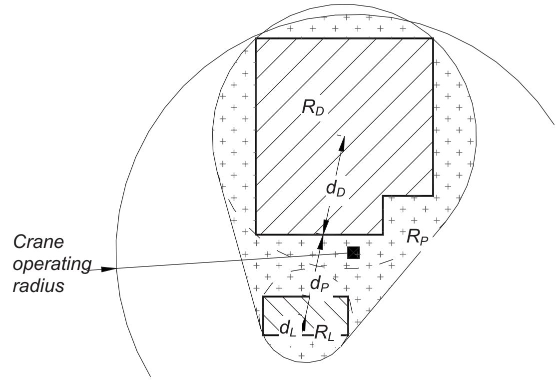

Fig. 6. Calculation of spatial exposure for object falling from crane

overlap time spent in that region. The factors may be assumed constant for all cases on the basis of observations or research (say 25%:30%:45%), but a more accurate approach is to estimate the path time according to the distance that must be traveled between each pair of loading and delivery regions. The additional step is as follows.

Step 4: Set T_L (average time to attach a load), T_D (average time to deliver a load), and $\bar{v}_h$ and $\bar{v}_v$ (the average horizontal and vertical speeds of the crane respectively) according to the task type. Compute the line joining the centers of gravity of the loading and delivery regions and measure the distances d_L, d_P, and d_D, as defined in Fig. 6. Measure the difference in elevation between the loading and delivery regions, h_{LD}, and calculate

$$T_P = \max(h_{LD}/\bar{v}_v; d_P/\bar{v}_h) \tag{4}$$

Finally, set

$$E_{Lj} = E_{Lj} \times \frac{T_L}{T_L + T_P + T_D} \tag{5}$$

$$E_{Pj} = E_{Pj} \times \frac{T_P}{T_L + T_P + T_D} \tag{6}$$

$$E_{Dj} = E_{Dj} \times \frac{T_D}{T_L + T_P + T_D} \tag{7}$$

Collapse or Overturning of a Crane, Concrete Pump, or Other Equipment

Collapsing or overturning equipment, such as tower cranes, mobile cranes, and concrete pumps, can impact on any location within the sector of a circle centered at the equipment's base. Fig. 7 depicts the situation. The area of the sector is defined by angle g, through which the equipment is operated, and the radius of the sector, wf_1, is equal to the distance of the furthest point on the equipment from its base. The area impacted by any particular event can be approximated by a swath of fixed width wf_2 stretching from the equipment's base outward to the outer perimeter of the sector. The probability of being exposed to harm at any point within the swath is therefore larger nearer the center of the circle than nearer its perimeter and, at any given distance from the center, it is proportional to the relationship between the width of the swath and the arc length at that distance. The probability of exposure for any given victim region, marked R_j in Fig. 7, is calculated by dividing the sector into concentric ring sections with radius to centerline r and width dr, calculating the exposure likelihood for each, and integrating across the whole sector. Thus, based on the generic expression for $E_{S_{ij}}$ [Eq. (2)], the probability of exposure is expressed as

$$E_{S_{ij}} = \int_0^{wf_1} \frac{wf_2}{r\phi} \times \frac{r\phi dr}{r\gamma dr} \times \frac{r\phi dr}{A_j} = \frac{wf_2}{\gamma A_j} \int_0^{wf_1} \phi dr \tag{8}$$

where ϕ = angle of the arc of each of the overlapping regions R_{ij}. Due to the difficulty of expressing $\phi = f(r)$ analytically for any given arbitrarily shaped region of activity for the potential victims (R_j), the algorithm computes the approximate probability using numeric integration and taking advantage of the ability of graphic software to perform Boolean intersection between regions. The procedure is to divide wf_1 into a fixed number n of intervals for dr and then compute

$$E_{S_{ij}} = \frac{wf_2}{A_j} \frac{wf_1}{n} \sum_{k=1}^{n} \frac{\text{area}(R_k \cap R_j)}{\text{area}(R_k)} \tag{9}$$

where R_k = circular band region of width $dr = wf_1/n$ at radius r_k and through angle g, as shown in Fig. 7. The area of each region R_k is simply $wf_1/n \times \gamma \times r_k$.

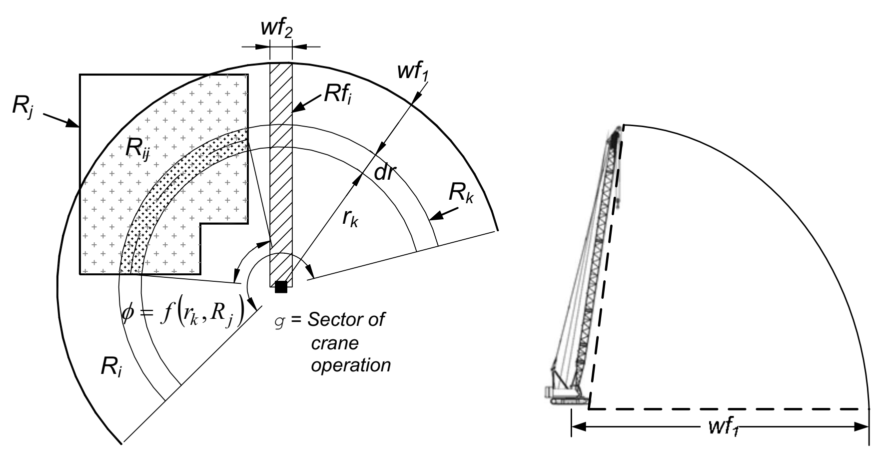

Fig. 7. Calculation of spatial exposure for equipment overturning

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Victim Region \ Source Region	1st floor	2nd floor	2nd floor balconies	3rd floor	3rd floor balconies	…	7th floor	Roof	South façade 1	South façade 2	…	Delivery area	Storage area	Site grounds
1st floor	1	0	0	0	0	….	0	0	0	0	….	0	0	0
2nd floor	0	1	0.008	0	0	….	0	0	0	0	….	0	0	0
2nd floor balconies	0	0.008	1	0.026	0.11	….	0	0	0	0	….	0	0	0
3rd floor	0	0	0	1	0.008	….	0	0	0	0	….	0	0	0
3rd floor balconies	0	0	0	0.008	1	….	0	0	0	0	….	0	0	0
…..	….	….	….	….	….	….	….	….	….	….	….	….	…..	….
7th floor	0	0	0	0	0	….	1	0.08	0	0	….	0	0	0
Roof	0	0	0	0	0	….	0	1	0	0	….	0	0	0
South façade 1	0.02	0	0	0	0	….	0	0	1	0	….	0	0	0
South façade 2	0	0.002	0	0	0	….	0	0	0	1	….	0	0	0
…..	….	….	….	….	….	….	….	….	….	….	….	….	….	….
Delivery area	0	0	0.02	0	0.03	….	0	0	0	0	….	1	0	0.011
Storage area	0.001	0.001	0	0.001	0	….	0.001	0	0.02	0.02	….	0	1	0.002
Site grounds	0.002	0.02	0.02	0.01	0.01	….	0.01	0.0005	0.03	0.03	….	0.011	0.002	1

Fig. 8. Exposure matrix for falling objects for the test building (Fig. 2)

Exposure Matrices

The raw output of the CHASTE method is the full set of possible exposures deriving from combinations of loss-of-control events with associated possible victim exposures. Each activity has multiple subactivities, each of which has different work tasks, which in turn each has many possible loss-of-control events, and each event has many potential victims. For example, an activity "construct fourth floor columns," with a subactivity "build formwork" and a task "install shoring," might have a loss-of-control event "shoring post falls," which can impact on the carpenters performing the shoring or on plumbers working on the ground level.

For any reasonably sized construction project there will be a very large number of exposures. The envisioned use of the CHASTE system is twofold: to allow management at all levels to both review the safety implications of construction plans at different degrees of resolution and with different filters, and also to perform "what-if" analyses of possible changes to those plans. Meaningful reporting is accomplished by filtering and summing the results in various ways—by crew, by accident consequence, by hazard type, etc.

As has been shown, the exposure algorithms perform fairly complex geometric calculations. Computation would be intolerably slow if they were executed for each exposure and every time an analysis was requested. The solution adopted was to compute all possible spatial exposure relationships a priori, at setup time for any new project, and to store the results in matrices. These precomputed "exposure matrices" store the exposure of every region to every other for each type of loss-of-control event. Their values are then read at run time instead of being computed.

A typical exposure matrix is shown in Fig. 8. It defines the exposures for falling objects for the building described in Fig. 2. The greatest exposure probability, 0.11, occurs for workers present in the second floor balcony region exposed to objects falling from activities performed in the third floor balcony region. The unit values (1) in the cells on the diagonal represent exposure of workers to the danger they pose to themselves.

Example and Reporting

Fig. 9 shows the method of calculation, and the result, for a typical loss-of-control event that could occur in the building project described in Fig. 2. This is just one of the large number of possible exposures for the project, but it serves to illustrate the method. For sake of simplicity, the intensifying factors have been excluded from the example: details of their use are provided in Rozenfeld et al. (unpublished data, 2007).

In the example, four formworkers busy erecting shoring on the fifth floor of the building, as part of the "formwork" subactivity of the "fifth floor concrete slab" activity, may drop objects during the course of their work. The normalized probability of objects dropping, 1.98, was drawn from the CJSA database. In parallel with this activity, four other workers are installing stone cladding on the south façade of the building. The exposure factor for these workers to the falling objects was calculated using the algorithm presented above and stored in the falling object exposure matrix; its value is 0.02. The temporal exposure factor is 0.9 and occurs during the period from December 1 to 6, 2006. The risk level calculated for this exposure event is 0.036.

Once the full set of exposures to loss-of-control events has been computed, the last step is to apply appropriate severity factors for each possible accident type and to produce reports. Users may determine what type of reports are desired—for example, a manager could request a plot of all the events that have the potential to result in death or injury over a given time interval. After any change to the activity schedule, the temporal exposure values

Hazardous Event #372	**Exposing Activity**	**Exposed Activity**
Activity	Concrete slabs	Stone cladding
Sub-activity	Erecting forms	Transferring stones
Start date	12/1/06	11/28/06
Finish date	12/6/06	12/6/06
Stage	Erecting the forms	Delivery using a hoist
Proportional duration	90%	100%
Location	Floor 5	South Façade
Trade	Form worker	Stone Cladder
Number	4	4

Loss-of-control type	Drop from crane	
Exposure Start	12/1/06	
Exposure End	12/6/06	
Time exposure factor	0.9	*100% x 90%*
Space exposure factor	0.02	*From spatial exposure matrix (Fig. 8)*
Exposure Level	0.018	*0.9 x 0.02*
Normalized expectancy of occurrence	1.98	*From loss-of-control database*
Normalized risk level	0.036	*0.018 x 1.98*

Fig. 9. Exposure calculation example for a loss-of-control event

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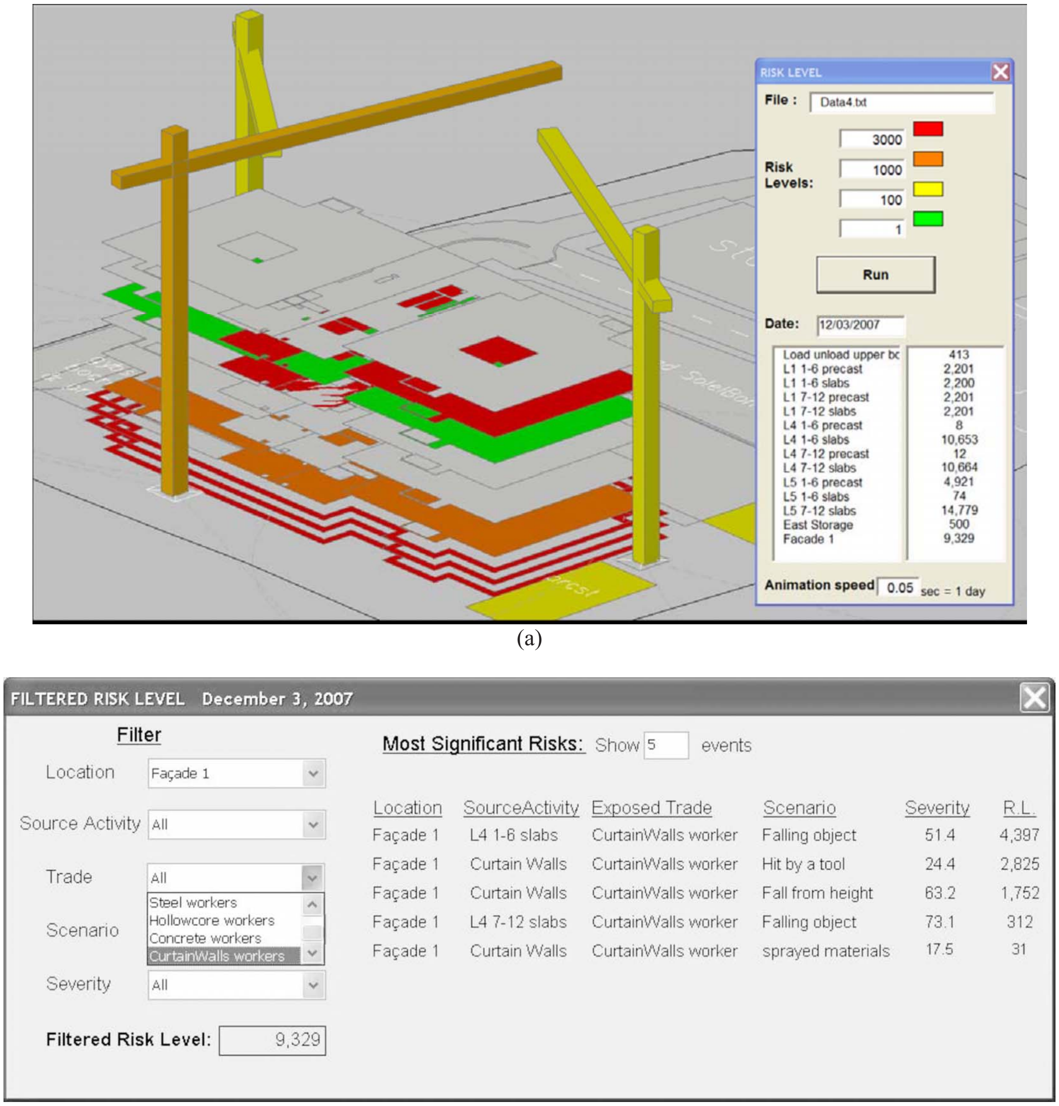

Fig. 10. (a) Generation of a 4D color-coded view of the locations with the highest levels of risk through time; (b) filtering of the most significant risks according to time period, location, source activity, trade, and accident scenario

could be updated and the reports regenerated rapidly because the spatial exposure values are stored in the matrices and do not need to be recalculated.

Implementation and Testing

The CHASTE method was implemented in software and tested during construction of an eleven story, 56,000 m^2 building containing offices, laboratories, and parking, built for an international semiconductor company. Almost all of the construction activities performed during the 8-month experimental period were covered by the system's database, including cast-in-place concrete slabs, columns and walls, precast hollow-core slabs, drywalls, masonry walls, exterior stone cladding, and curtain walls. The initial setup required preparation of a three-dimensional model of the building's spaces and addition of labor and location assignment codes to the construction schedule.

The system was run once at the master plan level and then integrated in weekly planning meetings, which required that an updated schedule be maintained. For the 8-month period as a whole, 46,000 possible exposures were identified. More than 62% of the events involved workers of different teams, with the remainder associated with exposure between members of the same team or self-exposure. The most frequent scenario type was "hit by a tool" and the most dangerous activity, with the highest volume of risk, was concrete slabs. The software provided project management with various output options. Fig. 10(a) shows a 4D CAD view that reflects the fluctuation of risk in intensity and location as a function of construction progress; Fig. 10(b) shows how a user can filter the view according to dates, location, source activity, trade, and accident scenario type.

Site personnel reported that the system contributed to better identification of exposures on site at the 1-month look-ahead planning level during the period examined. For example, it was revealed that the curtain wall workers would be exposed over a 10-day period to objects falling from height as a result of structural workers setting hollow-core planks on a deck five floors immediately above them. The sequence of the façades built by the curtain wall team was simply changed, completely removing the

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risk. Managers also identified significant benefit for safety planning at the master planning scale, as it can aid safety inspectors at the firm level to identify weaknesses across all of a firm's projects, to establish safety plans at the start of construction, and to update plans before each subsequent phase.

The experiment revealed two technical weaknesses. The first is that the knowledge base prepared for the experimental work must be expanded to cover additional construction methods that could not be accounted for. The second was that the project schedule maintained by the construction management team was neither detailed nor flexible enough for reliable forecasting of risks on a weekly basis.

Conclusions

The CHASTE method is a novel way to approach the task of safety planning in construction. Its two main innovations are that it explicitly accounts for

a. The exposures of workers to dangers posed by activities performed by other teams on site; and
b. The fact that risks and exposures change through time as the building and site topology change, and as crews arrive at, move between, or leave specific locations on site.

These two issues are the most significant distinguishing feature of construction safety when compared with safety in static factory conditions. Another innovation is that it calculates risk levels subject to the probabilities of occurrence of loss-of-control events established in extensive structured expert interviews using the CJSA approach; it is not dependent on accident statistics which are difficult to obtain and unreliable. Examples of the specific algorithms needed to implement the theoretical approach to computing exposure have been developed, implemented in a working prototype, and tested.

While an 8-month trial on a construction site has shown that the current CHASTE software implementation is applicable at the master plan level, it also showed that the accuracy of the risk forecasts provided for short-term detailed planning is limited by the reliability of the schedule data available. As a sophisticated method, CHASTE is likely to be most useful at the weekly level on sites where production planning is performed and schedules are reliably updated and followed, such as those using the Last Planner System. Testing at this level is being pursued currently on two further sites.

Future research must also address the need to validate the risk level forecasts. For validating estimated exposure levels, intensive work study observations can provide actual exposure data against which predicted rates can be compared for different exposure types and algorithms. Similar samplings can aid with validating the more frequent loss-of-control types.

Implementation of the CHASTE method will enable managers at all levels to rapidly compute the likelihood of exposure to dangers and the relative risk levels expected over any given time interval in a project. That information can help managers enhance safety in two ways. First, they can adjust construction schedules to avoid particularly risky exposures. The risk level computation can be repeated for any changed construction plan, with reporting at any desired level of detail, providing the feedback needed to assess the impact of schedule changes on risk levels and thus development of safer plans. This approach is called "risk leveling" because it is conceptually similar to resource leveling (rescheduling a project subject to a predetermined maximum resource level constraint). Risk leveling can be applied in advance, at the master plan level, or during a project, for shorter planning windows. Second, the information of where and when high risk levels are expected can guide them in applying their limited accident prevention, safety training, and/or inspection resources most effectively. The system essentially provides lean flow pull signals to ensure effective allocation of resources when and where needed, rather than the traditional push approach that applies resources at uniform rates.

Acknowledgments

This research was funded in part by the Office of the Chief Inspector of Occupational Safety of the Israel Ministry of Industry, Trade and Employment under Grant No. 2005902.

Notation

The following symbols are used in this paper:

A_i = area of region i;
A_{ij} = area of intersection of regions i and j;
A_{Wi} = area of Rw_i;
E_S = spatial exposure level;
E_T = time exposure level;
F_E = factors affecting the exposure level;
F_i = finish of subactivity i;
F_P = factors affecting the probability of loss-of-control event occurrence;
n_i = number of exposing workers;
n_j = number of exposed workers;
P = probability of loss-of-control event occurrence;
R_D = delivery region;
Rf = region of the extended perimeter of region i;
R_i = region i;
R_{ij} = region of the intersection of R_i and R_j;
R_L = loading region;
R_P = path region;
Rw_i = region from which a falling object will be dropped outside the region;
RL = risk level;
S = severity level;
S_i = start of subactivity i;
SD_m = task duration (percentage of total subactivity duration);
T_L, T_D, T_P = times of loading, unloading, and transporting an object using a crane;
wf_1 = distance from the edge of region i inward, from which a dropped object might fall outside the region;
wf_1 = radius of the affected sector;
wf_2 = maximum distance to which an object might be dropped from a region's perimeter;
wf_2 = width of the area affected by collapsing equipment;
γ = sector of crane operation (angle); and
ϕ = sector of overlap between the affected area and the exposed region (angle).

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