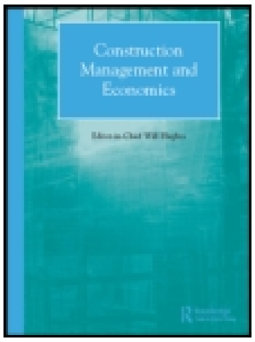

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'CHASTE': construction hazard assessment with spatial and temporal exposure

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CHASTE—'Construction Hazard Assessment with Spatial and Temporal Exposure'—is a conceptual model that enables forecasting of safety risks in construction projects for different trades, at appropriate levels of detail and reliability for different planning windows and managerial purposes, in a highly automated fashion. Unlike earlier models, CHASTE explicitly accounts for the fact that construction workers are frequently endangered by activities performed by teams other than their own. The risks to which workers are exposed change through time, as the activities performed and the physical environment of construction sites change. CHASTE uses a knowledge base of construction activities and probabilities of loss-of-control events, coupled with a project's construction plan and a digital building model, to forecast risk levels for work teams. It has been implemented in prototype software and tested on two projects.

Keywords: Construction safety, safety management, lean construction, risk analysis.

Introduction

Worldwide, the construction industry stands out conspicuously among all other industries as a primary 'contributor' to severe and fatal work-related accident statistics. The average fatality rate in construction, in terms of the number of fatalities per 100 000 workers per annum, is 14 to 15 in Europe (EASHW, 2001); 18 to 19 in the USA (Kartam and Bouz, 1998), and 20 to 22 in Israel (CBS, 2005). The average fatality rate for all other industries in western countries is just 3 to 4 (ILO, 2003).

Owing to their very nature, safety management is more difficult in construction projects than in stable work settings. Construction projects are dynamic, have frequent work team rotations, are exposed to changing weather conditions, and have high rates of unskilled workers. Unlike most industrial work environments in stable facilities, where production plans are closely controlled and individual tasks are well practised even when product mixes change, construction sites undergo continuous changes in site layout, in the topology and geometry of the facilities under construction, in the work conditions, and even in the design of work to be done. As a result, the levels of risk to which construction personnel are exposed vary greatly, as both the hazards and the degree of exposure change with time.

Griffel *et al*. (2007) found that, despite the recommendations in safety literature to perform frequent preliminary hazard analyses (PHAs) (Brown, 1976; Goetsch, 1996; Holt, 2001), the prevailing common practice in construction safety management is to invest resources (money, time, effort, etc.) in safety-related activities at a steady and uniform rate through each significant phase of a project, according to a generic long-range forecast of the risks at each phase. Similarly, Tang *et al*. (1997) found that intensive hazard analyses at construction sites are hardly ever performed. Where they are performed, hazard identification levels are often far from ideal (Carter and Smith, 2006), possibly owing to the lack of suitable tools. In general, the investment in safety includes acquisition of personal safety gear and collective safety equipment, employing safety administration personnel, and providing safety training and promotion materials. Actions taken to reduce risk levels are primarily motivated by the need to fulfil prescriptive legal requirements.

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In construction settings risk levels fluctuate with changes in the physical environment, with the changing nature of the works performed as projects progress, and with the turnover of crews and equipment. Thus uniform levels of investment in proactive safety measures can be illusive and inefficient. Instead, safety management resources (personnel and equipment) should be applied to enhance safety in accordance with the level of risk at any given time and place. Since construction project conditions and plans are also unpredictable in the short term (Radosavljevic *et al.*, 2002), this can only be achieved if risks are not only analysed in advance at a macro-scale, but also continuously monitored at a micro-scale as the work proceeds, for each time-phase and at each location.

If risk levels could be forecast reliably and easily, construction workers and managers (company safety manager, site engineer, project manager, superintendents, etc.) could better mitigate the risks in numerous ways:

- Adjusting master plans or weekly work plans, rescheduling or relocating activities in order to avoid peak risk levels that can occur when and where crews are endangered by the simultaneous activities of other crews, as shown schematically in Figure 1(a). This can be termed 'risk levelling' as it is conceptually similar to levelling resources in order to avoid over-allocation; it reschedules activities to avoid peak risk levels, as shown in Figure 1(b).
- Providing appropriate training and safety briefings close to the time of specific expected risks, and ensuring the use of safety equipment when needed (Rosenfeld *et al.*, 2006). Application of safety measures in direct response to risk levels (Sacks *et al.*, 2005) embodies the lean concept of pull flow control (Womack and Jones, 2003), in which products or services (in this case safety management) are pulled by actual demand (risk levels that represent workers' needs for safe work environments). Pull flow is in direct contrast to push flow, in which resources are applied according to long-range forecasts of demand.
- Changing construction methods or workers' positions where peak risk levels are identified.

However, risk levelling, pull flow control and other safety-enhancing interventions require the ability to predict long- and short-term risk levels at appropriate degrees of detail. Thus the primary goal of this research was to propose, implement a prototype of, and test a sophisticated yet user-friendly tool that enables both long- and short-term forecasting of safety risk levels, with less effort and with greater accuracy compared to the current methods. This required development of a new approach, which we have called the 'CHASTE' model (CHASTE is an acronym for 'Construction Hazard Assessment with Spatial and Temporal Exposure').

Safety risk assessment in construction

The general approach to risk assessment in construction as in other industries, as presented in the

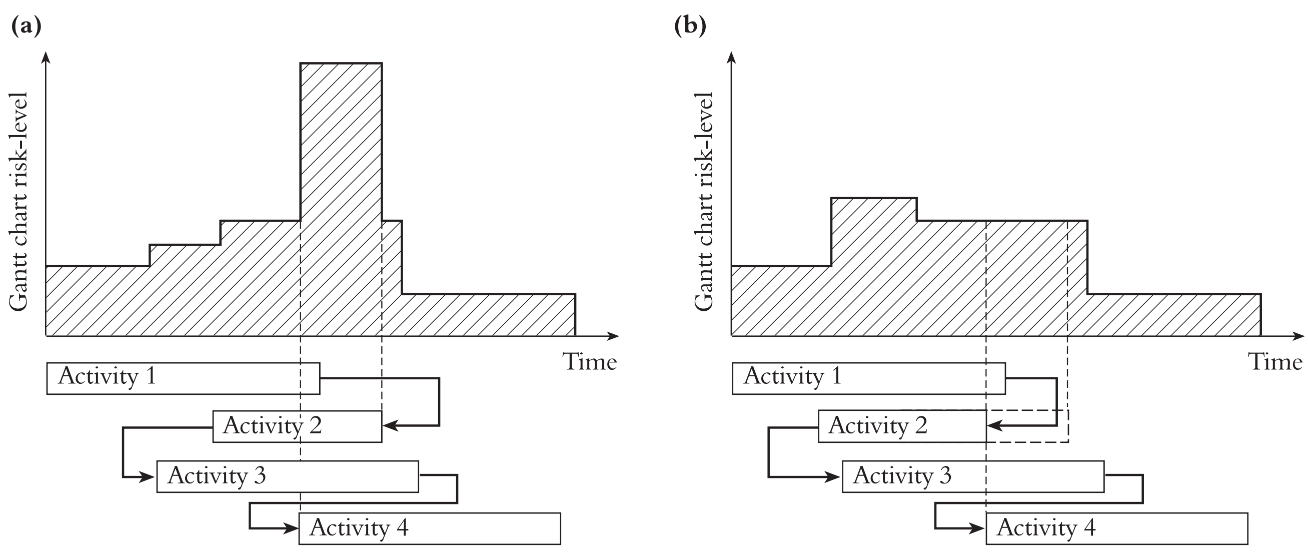


Figure 1 'Risk levelling'—rescheduling for safety
(a) Overlap between activities 2 and 4 generates a peak risk level because workers of activity 4 are exposed to a hazard inherent in activity 2
(b) Rescheduling activity 2 removes the overlap, thus eliminating the peak safety risk level

professional literature and standards (Hinze, 1997; ISI, 2000; PN-N, 2000; Holt, 2001; Manuele, 2005), is to identify the risks and then evaluate them by multiplying the likelihood of an accident by the potential severity of that accident. The difficult part of this approach is to evaluate the likelihood of any potential accident.

The first step is to identify and assess hazards for each specific kind of activity. Identifying hazards can be a complicated chore, because there are many different kinds of factors, and determining the relevance of each one is almost an impossible mission. In principle, statistical analysis of historical construction work-related accident data, seeking the numerical probabilities and severity levels for each type of accident, would be a straightforward way to evaluate the risks. However, this approach is problematic for two reasons: the likelihood of occurrence for most potential accidents is extremely small, and, as Gyi *et al.* (1999) pointed out, there is a high rate of under-reporting of accidents and near-misses. Thus very large sample sizes would be required to achieve statistical significance of the distributions obtained. Yet detailed information for assessing any kind of risk is rarely available (Warszawski and Sacks, 2004). Indeed, accident reports are becoming increasingly unavailable to researchers as a result of privacy protection laws. Fortunately, although assessment of risks is crucial for improving safety management, precise evaluation is not really necessary (Jannadi and Almishari, 2003); an estimated predicted level of the risks will suffice for the safety manager to take the correct actions.

A drawback of existing methods for risk assessment in construction (Jannadi and Almishari, 2003; Yi and Langford, 2006; Wang and Boukamp, 2007) is that they do not explicitly account for the fact that on construction sites, workers not only endanger themselves or others in their immediate vicinity; they also endanger other personnel who may be in the path of danger above, below or in the same general area. Falling objects, for example, are a particular hazard that is relatively unique to construction environments.

Hypothesis and method

In response to the need for safety risk forecasting in construction that is time and space dependent, we propose that:

> *Hypothesis 1*: Given existing information technologies, it is possible to forecast safety risks in construction projects for different trades, at appropriate levels of detail and reliability for different planning windows and managerial purposes, in a highly automated fashion.

To test this proposition, a prototypical system was designed, implemented and tested. This entailed taking the following steps:

(1) Development of a conceptual approach that would enable the calculations, including identification of all required components. The approach is detailed in the following sections.

(2) Research to establish the data required and to compile the knowledge base. This step employed the construction job safety analysis (CJSA) method (Rozenfeld *et al.*, 2007). The procedure is outlined below and use of the resulting construction safety knowledge base is explained in the sections 'Determining hazard levels', 'Calculating exposure' and 'Setting severity levels' below.

(3) Implementation of the software. The first prototype was implemented as a Visual Basic application that manipulates data from Microsoft Project, Microsoft Access and AutoCAD. The computing details are outside of the scope of this paper.

(4) Verification by testing of the prototype, first using the archive data for a small building project and then a full-scale test on a large and complex industrial project. The tests are described in the 'Application' section below.

Terms such as 'hazard', 'accident' and 'exposure' have been defined slightly differently by different authors writing on the subject of occupational safety in general and construction safety in particular (Covan, 1995; Hinze, 1997; Holt, 2001). For the sake of clarity, in Table 1 we define a set of terms as they are used in this paper. We also introduce a new term, 'loss-of-control event'. Every stage within each activity performed on a construction site has numerous typical 'loss-of-control' events associated with it, such as 'dropping a tool', 'falling from a ladder' or 'formwork collapse', and each such event has a distinct likelihood of occurrence dependent on team size, skill, space, climatic conditions and various other factors. The events are related to activities through the hierarchy as shown in Figure 2: each activity is divided into sub-activities, which are further divided into work stages. Each work stage has a set of possible loss-of-control events.

The CJSA method was developed specifically to meet the needs of the CHASTE model because the JSA (job safety analysis) or JHA (job hazard analysis) practice that is common in industrial settings (Chao and Henshaw, 2002), which focuses on self-endangerment, is not sufficient for construction. The CJSA method compiles a knowledge base that defines:

Table 1 Glossary of terms

Term	Definition
Accident	An unintentional event that causes bodily or property damage
Accident scenario	A hypothetical chain of events that may lead to an accident
Hazard	A work method, a piece of equipment, or a physical environment that bears the potential of triggering an accident
Loss-of-control event	An unwanted, unintended event in which control over a hazard is lost. A loss-of-control event may or may not result in an accident
Hazard level	The likelihood of loss of control of a hazard
Exposure	The presence of a potential victim (or victims) in a zone that may be affected in an accident scenario
Temporal exposure	Presence at a time during which a loss-of-control event may occur
Spatial exposure	Presence at a region at which a loss-of-control event may have impact
Regional exposure	Presence within a general region exposed to a loss-of-control event
Direct exposure	Presence directly within the potential strike path of an accident scenario
Self-exposure	Exposure to a risk that a worker creates by his/her own actions
Peer exposure	Exposure to a risk created by another activity performed at the same work area as the one in which he/she is present
Exposure level	The probability of being exposed

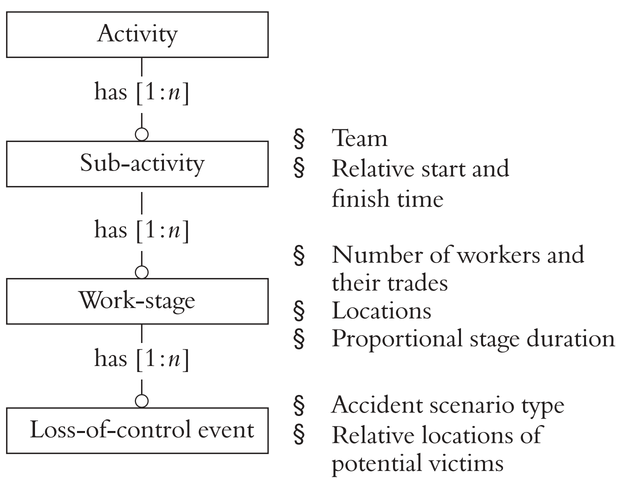


Figure 2 Primary object definitions in the CJSA knowledge base

- a work breakdown structure of typical activities, sub-activities, work stages and the possible loss-of-control events associated with them in the hierarchy shown in Figure 2;
- the likelihood of occurrence of each relevant loss-of-control event for each work stage;
- the most likely location of each construction worker during each work stage;
- the logical locations that are affected by various loss-of-control events caused by the detailed work stages of other activities;
- the probabilities of accident outcomes for each accident scenario that can arise from each loss-of-control event;
- the probabilities of use of personal safety equipment for each work stage.

The CJSA knowledge base must be prepared for each national or regional construction industry because it is dependent on local working culture. For the purposes of this research, a knowledge base was prepared for the domain of multi-storey buildings with reinforced concrete structures. The procedure entailed three steps:

(1) Intensive knowledge acquisition in a series of 10 half-day workshops with safety experts and senior construction superintendents, who are legally responsible for site safety, in which the patterns and nature of the risks of construction activities were identified and compiled in detail. Two researchers interviewed teams of four experts in each workshop. Seventeen activities were covered; they yielded 348 stages and 875 distinct loss-of-control events. This step provided the domain knowledge describing what loss-of-control events could be expected.
(2) An extensive field survey that included 101 interviews among 91 construction superintendents, in which estimates of all of the parameters used for assessing the probabilities of loss-of-control events, as well as their expected severities, were collected. This step provided the expected probabilities of the loss-of-control events identified in the first step.
(3) A series of interviews with 10 senior and highly experienced safety managers from leading large-scale construction firms to establish probabilities for the different accident scenario outcomes for the full scope of activities covered, and for the use of personal safety

Table 2 Five examples of event likelihood, including the most frequent and infrequent loss-of-control events

Activity	Sub-activity	Stage	Event	Average likelihood (occurrences per worker per year)
Cast-in-place concrete walls with stone cladding	Pouring concrete using a crane bucket	Filling bucket	Concrete spatter	168.0
Casting lightweight concrete for drainage	Casting concrete	Pouring the concrete	Dropping an object	91.3
Drywall construction	Erecting the framing	Attaching studs to exterior masonry or concrete walls	Spatter of debris from drilling or nailing	56.4
Exterior stucco	Manually applying an insulating layer	Curing and cutting protrusions	Struck by a tool	1.25
Cast-in-place concrete columns and walls	Installing forms	Cleaning and greasing forms	Fall from a ladder	0.060
Concrete columns and walls	Casting concrete with a crane	Lifting a bucket full of concrete	Crane collapse	0.0001

equipment. The safety managers were identified as the most reliable source of data because of their daily experience with safety management and accident investigations in construction.

Table 2 provides a brief set of examples of the results obtained in the second step.

The 'CHASTE' model

The 'CHASTE' model is a theoretical model for evaluating risk levels in construction or any other project-based production system with dynamic environments. It conceptually defines the required input knowledge and data, the mechanisms for manipulating the data, and the parameters that affect risk levels. The following formula, which presents the risk level as a product of three independent factors—hazard, exposure and severity—lies at the heart of the model:

$$RL_{ijk}(t) = HL_{jk}(t) \times EL_{ij}(t) \times SL_{ij} \quad (1)$$

where:

RL_{ijk} (t) = The total risk level caused by hazard k for team or worker i as a result of each loss-of-control event j to which the team/worker might be exposed at time t.

HL_{jk} (t) = Hazard level—the time-dependent likelihood of occurrence of loss-of-control event j caused by hazard k. There are two kinds of hazards: *active hazards*, created by ongoing activities, for instance transporting concrete using a crane; and *passive hazards*, caused by negligence or omission, for instance having an unsecured elevator shaft on the work floor.

EL_{ij} (t) = Exposure level—the probability that team or worker i will be exposed to loss-of-control event j. This probability changes through time, but it can be calculated explicitly for discrete time intervals. It consists of temporal exposure (being exposed to a hazard while it occurs) and spatial exposure (being at the exposed area).

SL_{ij} = Severity level—the total expected severity of the potential injuries for team or worker i for all of the accident scenarios resulting from a loss-of-control event j. Calculation of this factor includes consideration for the influence of safety equipment and protective personal safety gear.

Note that the terms are used as they are defined in Table 1.

The conceptual formulation of the CHASTE model is the basis for a software implementation. Figure 3 outlines the computational process. As can be seen, the model utilizes three main data sources:

(1) a comprehensive construction job safety knowledge base compiled using the CJSA method;
(2) a computerized construction schedule of the kind commonly maintained in most construction projects; and
(3) a digital building model of the construction site and the facility under construction.

The latter two are commonly available in BIM representations of construction projects (Eastman *et al.*, 2008), which include machine-readable representations of a facility's geometry.

Various managerial, personnel and environmental factors (such as management pressure to meet schedules, workers' familiarity with the site and the work, degree of crowding, weather conditions, etc.) that vary according to each project's context influence the

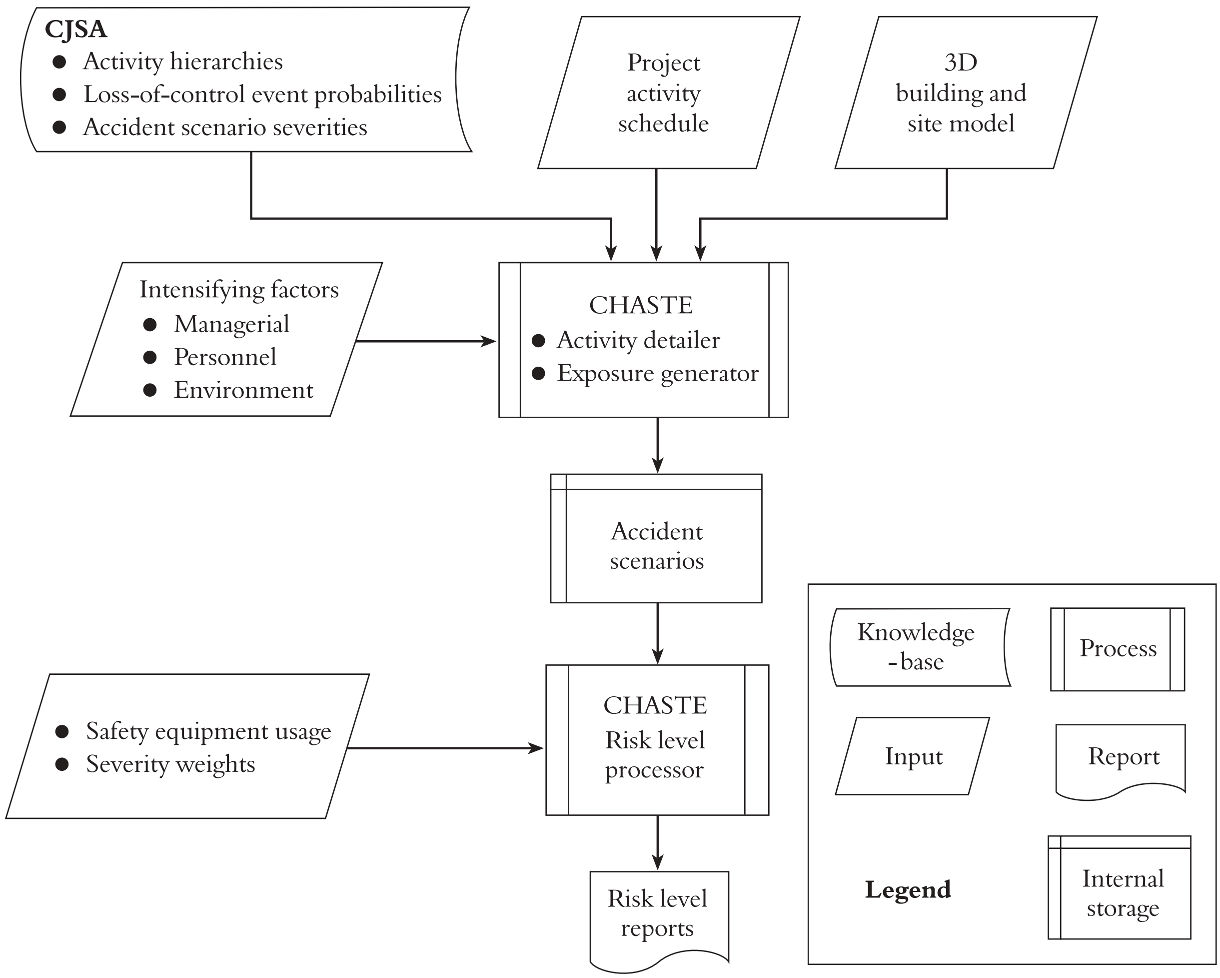


Figure 3 Conceptual flowchart for the CHASTE model

probabilities of loss-of-control events occurring and/or the probability of a victim being exposed to danger. These are factored into the computation of probabilities for every accident scenario generated by the activity detailer and exposure generator module. Once the accident scenarios have been detailed, the risk processor can evaluate risk levels by applying local information about the use of safety equipment and each user's subjective assessment of the relative weights that should be applied to different levels of severity.

The following three sections explain the approach to computation for the three parts of the CHASTE model: the likelihood of loss-of-control events, the likelihood of exposure to them for each potential victim, and the expected severity of possible accident outcomes.

Determining hazard levels

For the reasons outlined in the section 'Safety risk assessment in construction' above, the CHASTE approach bases assessment of risk levels on the likelihood of 'loss-of-control events' rather than on the likelihood of accidents. The likelihood of an accident is obtained by multiplying the likelihood of a 'loss-of-control' event by the probability of 'exposure' (the terms are defined in Table 1). By definition, the number of accidents is significantly smaller than the number of loss-of-control events. For every accident, there are numerous potentially dangerous events that end with no, or very little, damage.

To calculate the risk levels for any given duration of an activity on a specific project site, the first step is to determine which activities are being performed and by whom. A project schedule is the source for this information. For each activity, the CJSA knowledge base is queried to generate a detailed list of the sub-activities and stages and their associated loss-of-control events. The start and end times are determined at the resolution of the work stages by extrapolating from the activity start and end times in the schedule using typical start and end times and durations recorded in the construction method knowledge of the CJSA knowledge base.

The likelihood of occurrence for each loss-of-control event is recorded in the knowledge base for each individual work stage (e.g. 'pouring concrete') of each sub-activity (e.g. build concrete slab). The units for this measure are the number of occurrences expected per day, assuming continuous execution of that stage for a full working day. In any calculation instance, the likelihood of a loss-of-control event occurring during execution of a work stage is multiplied by the ratio of the duration of the stage to the duration of a day in similar units. If the likelihood must be aggregated over a whole sub-activity, it is weighted with the ratio of the duration of the stage to the duration of the sub-activity.

Calculating exposure

The exposure level depends on the type of activities performed and on the physical conditions at the site. The overall algorithm cross-checks information concerning expected regions of workers considering the expected timings of source and victim activities, searching for spatial and temporal exposure. The result of this entire process is the exposure level.

Two aspects independently affect the probability of a person or team being exposed to harm if a loss-of-control event should occur. The first is exposure due to presence at a region at which a loss-of-control event may occur (*spatial exposure*), and the second is presence at a time during which the event may occur (*temporal exposure*).

Spatial exposure

Spatial 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 in the path of harm.

Figure 4 illustrates the concept using a cause and effect diagram. For example, if a hammer is dropped from a height (a loss-of-control event), and a worker is present in the zone into which the hammer could potentially fall (he is regionally exposed), but it misses the worker (he was not directly exposed), then the result is a 'near miss' safety event. This distinction between accidents and 'near misses' is a common feature of accident causation models (Heinrich, 1980; Mitropoulos *et al.*, 2005).

There is no practical way to predict the exact location of a worker, and so direct exposure cannot be calculated. However, the nature of each activity is known (from the CJSA database), and therefore the distribution of a worker's presence in different zones on site can be analysed using the most detailed activity schedule available. Thus the probability of regional exposure can be computed.

Different specific spatial exposure algorithms are needed for different types of loss-of-control events, because the nature of the danger is different. Falling objects, for example, require that zones below the work zone be considered; horizontally adjacent zones and

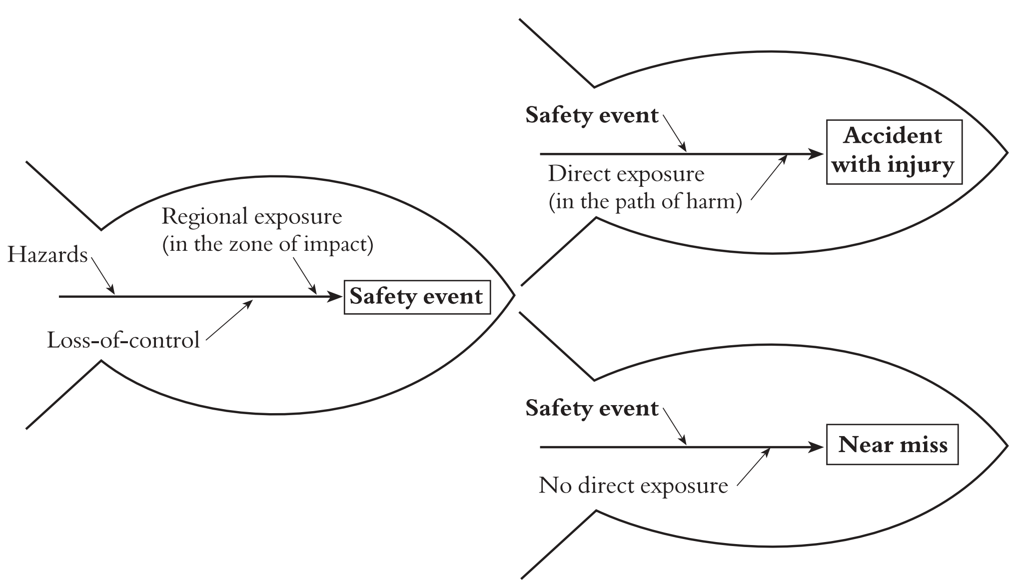


Figure 4 Cause and effect diagram illustrating the distinction between regional and direct exposure

zones above the work zone are relevant for fire, smoke and gas related incidents; a crane overturning will affect a zone within a specific radius of its base, etc. All of the algorithms are founded on the same two assumptions: (1) 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 is assumed to be uniform throughout that space; and (2) that the likelihood of a loss-of-control event impacting on any given location within the extents of the possible impact region is also uniform throughout that space. These assumptions allow the probability of spatial exposure to be computed using the proportions of the spaces, as stated in Equation 2:

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

where E_{Sij} is the probability of exposure in space; A_i and A_j are the areas of the source impacted region and the victim's task region respectively (regions R_i and R_j); Region $R_{ij} = R_i$ I R_j; $A_{ij} = area(R_{ij})$.

Figure 5 illustrates an example of analysis of the spatial and temporal (4D) exposure between a source zone in which a specific loss-of-control event could occur (in this case, the event of a piece of formwork, used for the construction of the building core at the top floor, falling from the crane) and a victim zone (in which other workers perform stone cladding on a scaffold on the west facade of the building). The hatched area in the figure is the region R_{ij}.

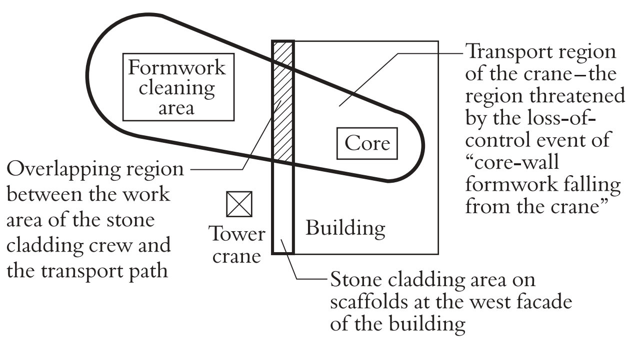


Figure 5 Example of a regional exposure overlap between a zone influenced by a loss-of-control event (a piece of formwork falling from the crane) and a region in which workers perform stone cladding

Temporal exposure

Temporal exposure occurs when there is the possibility of overlap in time between a sub-activity that is the source of a loss-of-control event (the source activity) and a sub-activity that involves a potential victim's presence in the dangerous zone (the victim activity). It is calculated by computing the probability of overlap between the times scheduled for execution of each of the detailed work stages of the source and victim sub-activities respectively, in any case at which two sub-activities occur at the same time (as defined in Figure 6).

The exact intervals in time at which each work stage will be performed cannot be specifically defined, because they are often repeated in a cyclical fashion within each work stage. They also do not necessarily start in the same sequence for each work stage. At the work stage level, the proportions of the source team's time spent performing the work stage is simply multiplied by the proportion of the victim team's time spent on the relevant work stage. Of course, the overlap must also be established at the aggregate level of the sub-activities in which each of the two work stages under consideration occurs.

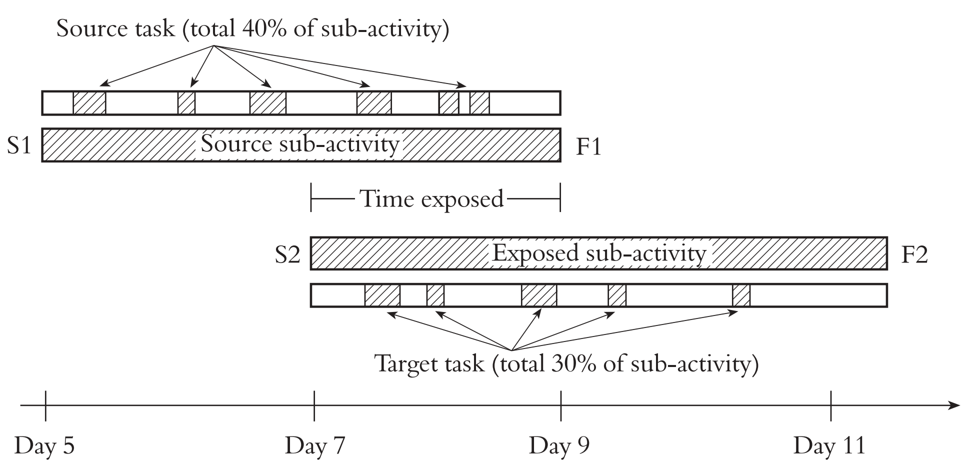


Figure 6 Exposure in time

At the level of detail of sub-activities, the planned start and finish times can be derived from a project's construction plan (which details the activities and their planned primary locations) and the CJSA knowledge base (which details typical sub-activities and work stages). The temporal overlap between the sub-activities can be calculated as follows, with reference to Figure 6:

- The source duration is S_1 to F_1, which are the expected start and finish times of the sub-activity that causes the loss-of-control event.
- The victim duration is S_2 to F_2, which are the expected start and finish times of the exposed sub-activity.

The exposure between the two overlapping activities begins at the later time $S_E = \max(S_1; S_2)$ and ends at the earlier time $F_E = \min(F_1; F_2)$. The temporal exposure level, $E_{T_{ij}}$, is defined as the product of the proportions of the total sub-activity duration for each work stage (taken from the CJSA knowledge base), multiplied by the number of workers involved in each, and is valid for the duration from S_E to F_E.

Finally, as stated above, the total exposure probability is the product of the probabilities of temporal exposure and spatial exposure, both calculated by considering overlaps between the workers or teams who generate the risk and the workers or teams exposed to the same risk. Thus for any specific time period during which sub-activities overlap, the total exposure level is given by:

$$EL_{ij} = E_{S_{ij}} \times E_{T_{ij}} \tag{3}$$

Note that direct exposure is not accounted for. As explained above, there is no practical way to predict direct exposure, and so CHASTE suffices with the accuracy that can be provided using regional exposure for the spatial exposure component. Also, the formulae and algorithms were developed thus far on the assumption that the source and the victim are separate and distinct. There are two special cases in which the distinction between source and victim does not occur, although the method is applicable without modification:

(1) Self-exposure, where a worker creates the risk to himself/herself by his/her own actions. In this case, both the temporal and spatial exposure probabilities are certain, and so the exposure probability is 100%.

(2) Peer exposure, where a worker is endangered by another activity performed at the same work area as the one in which he or she is present. In this case the spatial overlap is 100%, and the temporal overlap can be calculated in the usual way.

However, all of the procedures and formulae for calculating exposure up to this point are valid, without any change, for these two cases as well.

Setting severity levels

The third component of the risk level formula is the expected severity level, which is aggregated by normalizing the sum of the products of the probability of each possible outcome and the relative severity of each outcome. The expected use or non-use of personal safety equipment is also taken into account. The calculation of the severity level *SL* for each possible accident scenario *k* (where a worker is exposed to a loss-of-control event) can be expressed as:

$$SL_k = P[u]\sum_i w_i P[O_i] + (1 - P[u])\sum_i w_i P'\left[O_i\right] \tag{4}$$

where the terms are as follows:

$P[O_i]$ and $P'[O_i]$ are the probabilities of four possible outcomes O_i, when personal safety equipment is used $P[Ou_i]$ and when it is not used $P'[Ou_i]$. The possible outcomes considered use a scale similar in concept to that of Jannadi and Almishari (2003): light injury (up to one day of absence from work—scratch or wound); minor injury (longer absence from work—burn or fracture); severe injury with permanent disability; and death.

$P[u]$ is the probability that appropriate personal safety equipment will in fact be used, and conversely $1 - p[u]$ is the probability that it will not be used.

w_i is a relative weight assigned to express the severity of outcome O_i.

All of the values for $P[O_i]$, $P'[O_i]$, $P[u]$ are drawn from tables in the CJSA database. The values for w_i reflect the relative importance associated with each type of outcome. The CHASTE model intentionally refrains from proposing relative weights for the different ranks; the authors' view is that this must be a subjective value judgment made by each safety expert, or company, according to their principles or according to industry-wide policies.

Table 3 is an example of the detailed calculation of severity level for a scenario in which a worker who is installing formwork is struck by material falling from a palette or bucket transported by a crane. In this example, the probability of wearing a helmet is 77%; naturally, any specific user could override the values to reflect the degree of discipline of their own or of their

Table 3 Example of calculation of the expected severity for a scenario 'struck by material transported by a crane' while 'assembling industrial forms for concrete slabs'

Severity level	Severity weight	Expected occurrence (%)		Weighted severity level
		With safety equipment (77%)	Without safety equipment (23%)	
(1) Light injury	1	70	50	0.7
(2) Medium injury	5	25	41	1.4
(3) Severe injury	25	3	7	1.0
(4) Death	100	2	2	2.0
Scenario severity level				5.1

subcontractors' employees in terms of use of safety equipment.

Application

A prototype software implementation of the CHASTE model was prepared and tested on two different construction projects. The first was a seven-storey residential building with 3000m^2 floor area. Eight activities were analysed using the CHASTE method (automatic detailing of loss-of-control scenarios using the CJSA knowledge base, computation of exposures through linkage to a 4D model of the construction progress, and calculation of risk levels incorporating severity levels for every loss-of-control scenario). The activities analysed, through a total duration of six months, were: floor tiling, concrete slabs, stone cladding, concrete columns and walls, piling, drywalls, roof sealing and waterproofing. The system produced a list of 5424 possible accident scenarios. The most hazardous activity was 'concrete slabs'; its most dangerous work stages were forming and reinforcing the slabs. The most hazardous loss-of-control event types were: struck by a tool, objects falling from a crane, and falls from height. The proportion of events that impacted on crews and workers other than those generating the hazard was 63%; 37% concerned self-inflicted risks.

The second project consisted of high-tech labs and offices for an international semiconductor company (Figure 7). The building has five underground floors and six above-ground floors with a total built area of over 56 000m^2; the total construction cost was estimated at $80 million. The building's structure is cast in situ concrete with precast hollow-core floor slabs. Primary finishing activities included interior masonry walls, drywalls, electrical and communication networks, plumbing, HVAC installations and elevators. The facade activities included curtain walls and stone cladding. Three tower cranes were used and the number of workers on site fluctuated from 100 to 200, depending on the stage of construction. The CHASTE analysis covered all the structural activities, masonry,

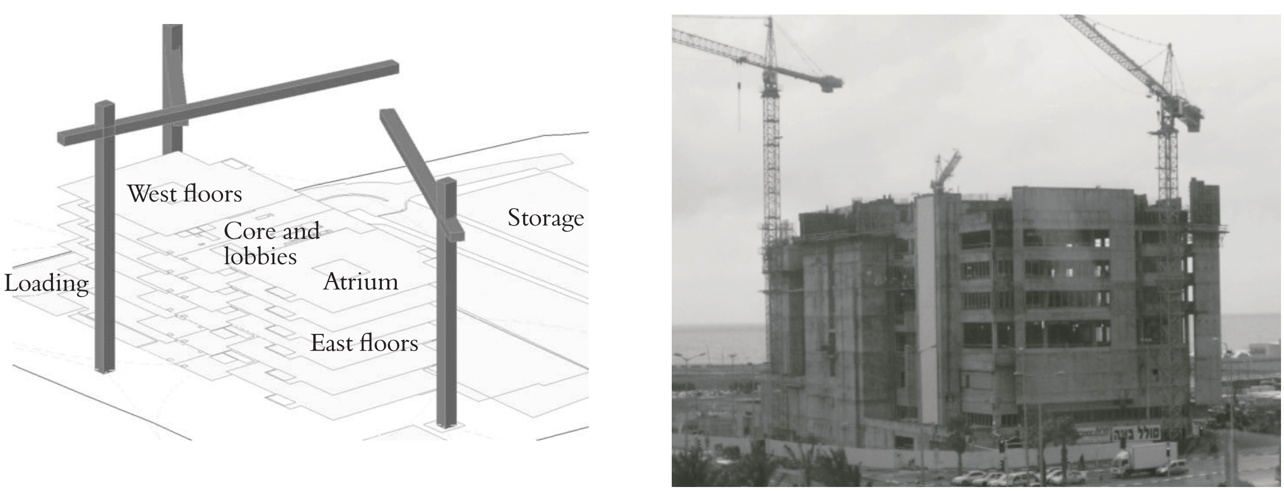


Figure 7 A 3D view of the regions defined for the semiconductor research building, and a site photo taken near the completion of structural works

drywalls and curtain wall facades for the floors above ground.

At the start, a total of 39 different regions were defined in the building and on the site: 24 within the building, according to zones defined in the schedule, eight regions outside the building (storage, loading areas, offices, etc.) and seven equipment regions (cranes, concrete pumps, etc.) Each region was defined by a code, perimeter geometry, area measure and elevation.

Once set up, the CHASTE program was run each week and results were summarized. The total number of all possible scenarios predicted was 45 840. Table 4 shows a small sample of these, selected from a one-week period. The scenarios in the table with only one line for the work stage detail are self-exposure cases, while those with two lines show the source and target work stages on the first and second lines respectively. The details of the specific trades of the workers involved in each scenario have been omitted from the table owing to lack of space, but this information is included in the raw output. A user would not be expected to work directly with these data, but rather would use reports that aggregate the data in different ways. For example, one might wish to aggregate the risks to a particular trade over a particular day, as is done for curtain-wall workers in Table 5.

The most hazardous single event was 'hit by a tool' while erecting scaffolds for concrete slab formwork support, and the most dangerous activity type in terms of volume of risk was concrete slab construction. The most endangered trades during this period were form workers and steel reinforcing workers. The most hazardous scenario type was 'fall from height'. More than 62.5% of the predicted hazardous events were caused by some worker other than the one exposed. After each analysis run, the results can be filtered, analysed and reported in a variety of ways, according to region, victim or source team or trade, severity level, accident scenario type, etc. Figure 8 shows just one example of the many kinds of report that can be generated. This chart shows the total predicted risk level according to region on site for a two-week period. This kind of output helps in identifying and levelling risk peaks during the master planning. Another important report type that can be generated is a colour-coded animation of the overall risk level in each region over any given period, shown on a 3D building model view. The regions are coloured according to risk level, varying from green (least hazardous) to red (most hazardous).

Conclusions

The CHASTE model is a novel approach for predicting risk levels in support of proactive safety management at construction sites. It is a time- and space-dependent model that can quantify risk levels by means of automated calculations, which enables more efficient management of construction safety. The meticulous job safety analyses of common construction tasks carried out using the CJSA approach have yielded a substantial knowledge base of loss-of-control events and their probabilities for most of the activity types common in reinforced concrete construction. The research to date has included development of the concept, workshops and interviews to build the knowledge base, implementation of a prototype software application, and tests of the software in two construction projects.

Ostensibly, the proposition that 'it is possible to forecast safety risks in construction projects for different trades in a highly automated fashion' has been demonstrated. However, two aspects remain to be verified: to what degree do the predicted safety risk levels correlate with safety performance, and what are the practical impacts of use of the tool on safety management in construction.

The first aspect is difficult to test for because it is impractical to fully record all of the very high number of loss-of-control events and exposures that occur on any typical site. Validation using accident statistics is also very difficult because the number of loss-of-control events and exposure scenarios that actually result in reported accidents is extremely small; in any case, accident statistics cannot be representative of any one site, and every construction project is unique.

The number of activity types that were surveyed during the CJSA in this research is only a sample of the total number of activities and methods employed on a typical construction project, and therefore, the model as implemented to date cannot yet give the whole picture at once. Further research is needed to expand the number of activities analysed. Although over 80 different construction supervisors were interviewed in the CJSA process about the trades they know best, the number of responses for each loss-of-control event, for each sub-activity and for each activity type was not large enough to allow conclusions about their distributions. In order for CHASTE to be implemented extensively, the CJSA step would need to be performed for steel or precast structures, and refined in each country, region or city, depending on local construction culture.

With a reliable and fairly precise prediction of safety risk levels, construction managers will be able to level risks by rescheduling tasks and/or by providing other solutions to reduce risks to acceptable levels. This can be done before construction starts to make master plans fundamentally safer for execution, as well as an ongoing process on site in periodic work planning

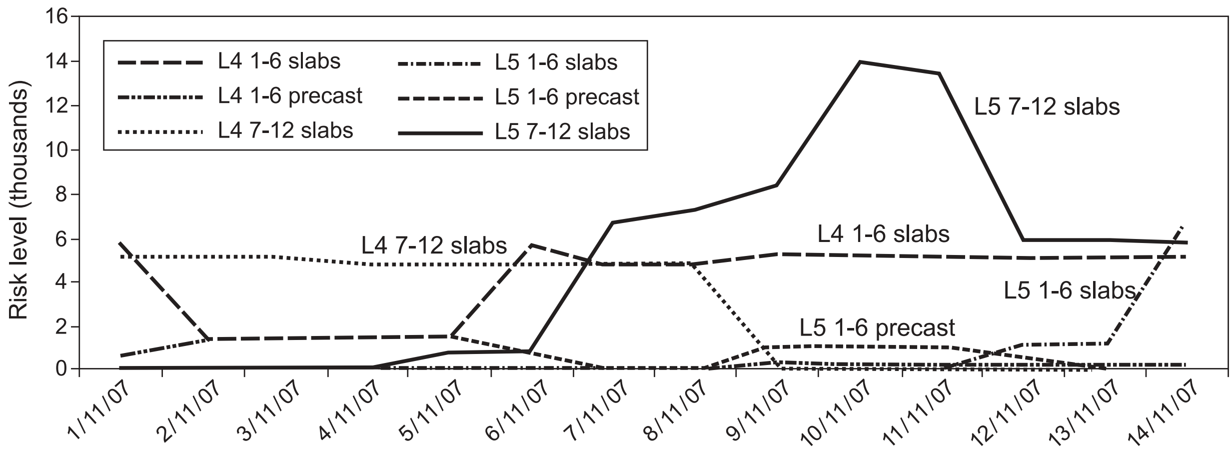
Table 4 A sample of the raw scenario output for the week of 14 to 19 January 2007, showing a single example for each of a selection of scenario types

Scenario type	Task	Sub-activity	Stage	Duration	Time %	Location	Temporal exposure	Spatial exposure	Severity	Risk level
Collapse	Machine room slab	Pour concrete	Placement and vibration	17/1–18/1	70	Roof	100	100	64.9	29
Concrete pump overturn	Machine room slab	Pour concrete	Pumping concrete	17/1–18/1	70	Crane	63	9.2	105	3.0
	Stone facing north elevation	Laying stone	Apply glue to stone	1/1–8/2	90	South facade				
Electrocution	Machine room slab	Plumbing/ Electrical	Installing pipes	15/1–16/1	100	Roof	100	100	112	123
Fall from a ladder	Drywalls 3rd floor	Framework	Install ceiling channels	14/1–17/1	100	Floor 3	100	100	9.9	272
Fall from height	Sealing balconies L4	Sealing	Install vents	19/1–22/1	5	Balcony 1	100	100	109	189
Falling materials or tools	Machine room slab	Plumbing/ Electrical	Installing pipes	15/1–16/1	100	Roof	20	100	1.0	38
	Machine room slab	Upper rebar & supervision	Tying steel	16/1–17/1	20	Roof				
Formwork collapse	Machine room slab	Plumbing/ Electrical	Installing pipes	15/1–16/1	100	Roof	90	2.0	72.7	46
	Machine room slab	Formwork assembly	Formwork assembly	12/1/07	90	Floor 6				
Run over by a vehicle	Machine room slab	Pour concrete	Concrete pump entrance/exit	17/1/07	20	Delivery	100	100	105	7.6
	Machine room slab	Pour concrete	Concrete pump set-up	″	10	Delivery				
Slip	Machine room slab	Curing	Curing	18/1/07	100	Roof	100	100	2.6	12
Struck by crane load	Machine room slab	Lower reinforcement	Transport rebar meshes	14/1–16/1	20	Open storage	100	100	2.6	15
Struck by hand tool	Machine room slab	Lower reinforcement	Manual placement	14/1–16/1	60	Roof	100	100	105	278

Notes: Scenarios with a single row are self-exposure; scenarios with two rows show the source task detail in the upper row and the target task detail on the lower row.

Table 5 The five most significant risk scenarios identified on a particular day for a curtain-wall worker

Region of risk	Source activity & region	Scenario type	Severity (1–100)	Cumulative risk level
Facade 1	L4 1–6 slabs	Falling object	51.4	4397
Facade 1	Curtain walls facade 1	Hit by a tool	24.4	2825
Facade 1	Curtain walls facade 1	Fall from height	63.2	1752
Facade 1	L4 7–12 slabs	Falling object	73.1	312
Facade 1	Curtain walls facade 1	Sprayed material	17.5	31



	1/11/07	2/11/07	3/11/07	4/11/07	5/11/07	6/11/07	7/11/07	8/11/07	9/11/07	10/11/07	11/11/07	12/11/07	13/11/07	14/11/07
L4 1-6 slabs	5687	1413	1413	1412	1555	5689	4939	4939	5217	5104	5104	5104	5118	5118
L4 1-6 precast	687	1390	1390	1390	1521	851	102	102	342	239	239	243	256	256
L4 7-12 slabs	5143	5134	5127	4831	4846	4838	4838	4832	22	19	19	19	–	3
L5 1-6 slabs	–	–	–	–	45	66	68	87	87	30	29	1058	1058	6774
L5 1-6 precast	–	–	–	–	38	38	38	62	1076	1021	1021	499	–	–
L5 7-12 slabs	16	16	16	16	851	851	6639	7311	8400	13917	13325	5870	5870	5730

Figure 8 CHASTE results: Risk level chart according to regions for the period from 1 November 2007 to 14 November 2007

meetings. The definition of a mature task for execution used in the Last Planner System can be extended to include the requirement that it must be safe.

The primary practical limitation discovered during the tests on site concerns the approach to using the planned construction schedule as an information source. On sites using traditional planning methods, the dynamic nature of construction lead to plans ceasing to resemble the actual work, which would render CHASTE irrelevant. The method relies on performance of production planning at a detailed level with (at least) a weekly work plan being prepared with all trades being updated in commercial software for that purpose. If the information system is updated for other management purposes and not specifically for safety management, there is no additional overhead.

An important limitation is that the CHASTE model does not account for all of the human factors at play in construction safety that may affect the likelihood for loss-of-control occurrence or the level of exposure. While future research could establish the influence of various human and other factors on the risk level (in a fashion similar to that pursued by Hinze *et al.* (1998)), it is only factors whose information can be collected automatically (such as the weather, first day on site, workers' experience, schedule delays, etc.) that can be used effectively. Other factors, (such as workers' personal characteristics, workers' physical and mental state, etc.) cannot be used. We reiterate therefore that risk assessments must be made by people and not by software.

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