LEAN SCHEDULING FOR SAFETY: DEVELOPMENT OF A TIME-DEPENDENT RISK LEVEL MODEL

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ABSTRACT

This paper presents ongoing research toward a conceptual model to support an advanced proactive safety management approach that is efficient not only in terms of the resources it requires, but also in terms of its impact on construction process flow. The model is based on the understanding that the risk levels to which workers are exposed, change through time. Accident risk levels are dependent on human factors, physical hazards, environmental factors and organizational/business factors. Many of these are time-dependent and their values can be derived from construction schedules (at various levels of detail, from the master schedule down to the weekly work plan). The model enables forecasting of risk levels for work teams and individual workers as a function of time. Forecasts will be available at different levels of planning windows.

In implementation, the model will enable two main enhancements to project planning. First, in planning activities, the safety level resulting from combinations of activities planned to be performed simultaneously can be evaluated and manipulated (lowered, or peaks avoided) by safety-conscious scheduling. In many instances process flow can be enhanced if accident prevention measures can be made redundant by avoiding particular combinations of simultaneous activities. For example, an acceptable impact on overall risk level may be added as a consideration for releasing work for execution in a Last Planner meeting. Second, the activities and effort of those responsible for site safety can be 'pulled' by peaks of high risk levels. The goal is a dynamic, 'lean' level of effort invested in safety management, eliminating the 'wasted' effort inherent in standard practice, where a steady and uniform investment of accident prevention effort is applied throughout the project duration.

KEYWORDS

Hazard, Risk level, Safety

INTRODUCTION

Enlightened clients demand excellent safety performance from construction contractors, and achieving safe projects requires effort. Accident prevention activities do not add commercial value to buildings directly, rather they reduce risk and are motivated by moral values. Lean thinking suggests that the activities undertaken to promote occupational safety and health in construction can be improved—that waste can be identified and removed and that negative impacts on process flow can be minimized.

A "hazard" is a state or condition that can lead to injury, illness or death, property damage, damage to the work environment, or a combination of them; a "risk" is the product of the probability of occurrence of an accident and the severity of the expected outcomes (ISI 2000). In almost every country around the world, the construction industry stands out among all other industries as the main contributor to severe and fatal accidents (Ahmed et al. 2000; Gyi et al. 1999; Kartam and Bouz 1998; Shepherd et al. 2000). In Israel, for example, there are about 150,000 construction workers (CBS 2004). On average, 30 of them are

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killed every year in work-related accidents. This statistic puts a worker employed 25 years in construction at a risk of roughly 1 to 200 of dying in a construction accident. Over the past nine years, about half of all occupational fatal accidents in Israel occurred in the construction industry (LOSH 2005), although the number of workers it employs is only 8% of all the workers in the economy (CBS 2004).

Many theories of accident causality have been published so far (Hinze et al. 1998; Kartam and Bouz 1998; Saloniemi and Oksanen 1998). The most prominent among them are the Accident-Proneness Theory, the Domino Theory, the Goal-Freedom-Alertness Theory, and the Occupational Hygiene Model (Heinrich 1980; Hinze 1997). However, none of them deals with the time-dependent nature of risk levels, nor do they confront the problem of waste in construction safety management. Blumenthal (1968) developed a time-related road accident causation theory that relates fluctuating levels of network performance demand along the route (changing levels of design, roadway types, traffic flow rates, etc.) to the driver's performance level, which also varies with time (because of factors like fatigue, lack of attention, illness, etc.) An accident is most likely to occur when the performance level of the driver is not compatible with the performance demands of the network (Mahalel 1982).

Organizational pressures to increase productivity and individual worker's natural drive to decrease effort push workers to work near the edge of safe performance (Mitropoulos et al. 2003). The most common managerial practices that construction companies use to promote safety are reactive, which means performing safety related activities after accident events (Hansen 1993; Saurin et al. 2004). Few of the construction companies undertake proactive measures (pre-task hazard analysis). The educational and motivational effort to work safely usually defers to the organizational necessity to increase productivity and to the worker's urge to spend less effort (MacCollum 1990; Mitropoulos et al. 2003).

Most common strategies apply safety-related activity at constant levels through project duration, without distinguishing between activities and accounting for varying external conditions. A steady and uniform investment of activity is maintained throughout project duration. For example, consider safety inspections: if the safety manager of a construction company had accurate data concerning the weak spots of the project, he could plan the inspections more expediently.

Some important proactive actions can be taken in order to reduce risk levels; one action, possibly the most important, is to identify all relevant hazards for each specific kind of activity (Hyo–Nam et al. 2002; ISI 2000). Preconstruction risk assessment is an efficient proactive measure (Hoxie 2003); however, identifying hazards can be complicated, because there are many different kinds of factors, and determining the relevance of each one is very difficult (Cuny and Lejeune 2003). Most common factors that have a substantial influence on most construction projects are time dependent. Knowing the level of risk as it changes through time would help contractors identify high risk construction activities and would enable them to allocate safety precautions more efficiently (Jannadi and Almishari 2003).This is the goal of the ongoing research reported here. The next section introduces the theoretical model, after which the second phase—data collection and validation—is described. The penultimate section describes a lean safety management strategy based on the theoretical model. theoretical model A proactive safety policy (identification and assessment of risk factors) is a more efficient way of managing safety in order to prevent accidents than a reactive policy (Harper and Koehn 1998; Saurin et al. 2004). The paper presents a conceptually advanced model to support a proactive safety management approach. The model considers that, at any moment during a construction project, the risk level changes and each individual worker is subjected to different hazards. Each worker also has changing performance levels. Therefore, every moment requires appropriate specific actions that can help reduce the probability of an accident; this also implies the converse, i.e. that inappropriate treatments are a waste of resources -activities that do not provide value (Womack and Jones 2003).

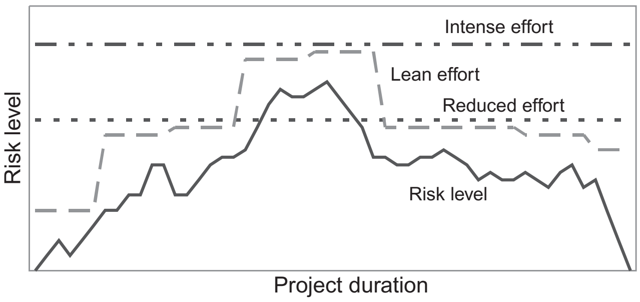

Figure 1: Risk level and safety effort strategies through time

Figure 1 describes a hypothetical fluctuation of the risk level at a construction site through time. The two horizontal lines express two alternative constant levels of investment in safety related activities. The upper line presents an intense safety effort that covers the highest point of risk level. This strategy is effective, but wasteful. The lower line presents a more practical strategy with a reduced effort that covers the risk level most of the time; however, some risks remain uncovered. This strategy is less wasteful, but may be ineffective. According to the approach proposed here, safety effort should be matched to the risk level as it changes, as shown by the stepped dashed line labeled "Lean effort". The risk level can be said to 'pull' the safety effort, rather than 'pushing' predetermined safety activities.

The ability to assess future fluctuation of risk levels is essential for development and implementation of a dynamic safety strategy. The assessment model must take a multitude of time dependent factors into account. The probability of an accident of any particular type (e.g. falling, burn, collision) occurring depends on the combination of different types of construction activities executed at the same time (each type entails specific hazards), the physical state of the facility under construction, external conditions, and personal conditions of the workers involved. This probability may increase due to particular combinations of some hazards and factors, or decrease under other combinations; it may behave differently under certain combinations occurring at specific times, more than at another times (Fang et al. 2004; Sawacha et al. 1999). Since there are no apparent analytical ways to define such relationships, an empirical model must be developed. Statistical data of accidents that actually occurred in the past can be used to identify the most significant combinations of factors and hazards for the main types of accident risk that appear in almost any construction site.

Table 1 presents a preliminary set of hazard and factor types and timings developed for this project. These are the hazards and factors that are likely to appear when accidents occur (Hinze 1997; Perry 2003). In Table 1, the factors are divided into four groups that follow the '4M' (Man, Machine, Media and Management) classification: 1) human factors such as training level, I.Q., risk aversion, and alertness; 2) Physical hazards such as work at heights, equipment, noise, fire; 3) Environmental factors such as precipitation, heat, wind and dust; 4) Company (commercial/organizational) factors such as time pressure, contractual conditions, supervision, and legal responsibilities. Some factors are static and can easily be predicted, others are time-dependent, but most are activity-dependent (such as work at heights, welding, and noise). In some cases, company-wide policies determine whether a factor will be relevant on a site or not.

The time-dependent risk level for any particular accident type is modeled as a function g of the hazards and factors (Table 1), as defined in equation (1). The overall risk level can be expressed as a mathematical combination of the individual levels of time-dependent risks, as defined in equation (2), and shown schematically in Figure 2. The relationship between the overall risk and the individual risk levels is not obvious and must be investigated. The bold solid line in Figure 2, which represents the overall risk level through time, is called the "overall risk envelope".

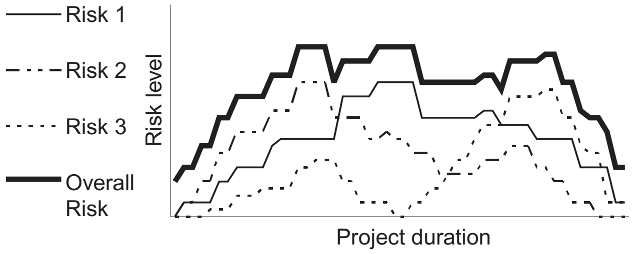

Figure 2: Time dependent risk envelope

$$r_i(t) = g\begin{bmatrix} H_1(t), H_2(t), \ldots, H_j(t) \\ P_1(t), P_2(t), \ldots, P_k(t) \\ E_1(t), E_2(t), \ldots, E_l(t) \\ B_1(t), B_2(t), \ldots, B_m(t) \end{bmatrix} \quad \ldots\ldots\ldots (1)$$

and

$$R(t) = f[r_1(t), r_2(t), \ldots, r_i(t)] \quad \ldots\ldots\ldots\ldots (2)$$

where;

$R(t)$	Time dependent total risk level function (empirical units)
$r_{j(t)}$	Time dependent risk level of accident type *i*. Examples of types are falling from heights, burns, electrification.
t	Time (date or hour)
$H_{j(t)}$	Human factors such as training level, I.Q., risk aversion, and alertness.
$P_{k(t)}$	Physical hazards such as work at heights, equipment, noise, fire.
$E_{l(t)}$	Environmental factors such as precipitation, heat, wind and dust.
$B_{m(t)}$	Company (commercial/organizational) factors such as time pressure, contractual conditions, supervision, and legal responsibilities.

This paper further proposes that the same approach can be applied at different degrees of resolution of any construction project, as presented in Figure 3. The different levels have different risk overall risk envelopes, and different risk compositions. For instance, although groups of workers may be exposed to similar hazards, Table : List of hazards and factors influencing accident probability

Factor/ Hazard Group	Factors or Hazards		Activity dependent	Time dependent	Static	Policy dependent
Human (Personal) Factors	2.1	Experience (years)			✔	
	2.2	Personal level of risk aversion			✔	
	2.3	Personal discipline			✔	
	2.4	Understanding of primary site language			✔	
	2.5	Level of alertness		✔		
Physical Hazards	2.1	Hazardous materials	✔			
	2.2	Work at height	✔			
	2.3	Work close to power-lines	✔			
	2.4	Scaffolding	✔			
	2.5	Access to stored materials		✔	✔	✔
	2.6	Site topography		✔		
	2.7	Excavation	✔			
	2.8	Open flame or heat source	✔			
	2.9	Explosives	✔			
	2.10	Use of lifting equipment	✔			
	2.11	Support towers	✔			
	2.12	Unstable structures	✔			
	2.13	Welding	✔			
	2.14	Obscured work area	✔			
	2.15	Overlapping between cranes	✔			
	2.16	Overlapping between crews	✔			
	2.17	Inadequate working platforms	✔			✔
	2.18	Disordered work-environment	✔			✔
Environmental Hazards	3.1	Dust	✔			
	3.2	Noise	✔			
	3.3	Darkness		✔		
	3.4	Ventilation conditions		✔		
	3.5	Precipitation		✔		
	3.6	Extreme temperatures		✔		
	3.7	Wind		✔		

each individual worker will have different factors that influence their chances of becoming involved in an accident, such as level of training, time pressure, and personal level of risk aversion. The first advantage of this approach is that accident prevention activities can be focused specifically to workers in greater danger; the second is that it can be used to reschedule or reassign activities so as to reduce peak risk levels.

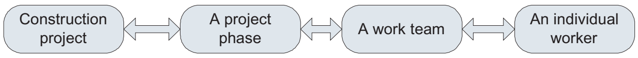

Figure 3: Different managerial levels for implementing the risk envelope model

DATA COLLECTION AND FUTURE RESEARCH STAGES

In the next stage of the research described here, data will be collected for accidents that have occurred in the past five years. Each year, about 3,000 severe construction work-accidents are reported to the Israel Labor Inspection Administration. At least 400 reports will be selected at random from this database, and the site superintendents who were present at each site at the time of each accident reported will be interviewed. The interviews will be structured using a detailed questionnaire that will endeavor to establish the presence of hazards and their impacts, resulting from the full range of activities performed on the site before and during the accident.

The site superintendents are the most appropriate source to provide the necessary information about the accident for two reasons: 1) Formally, they are responsible for all safety issues on-site, thus they are certain to have been involved in the investigation that followed the accident; 2) Due to their key role in the practical execution of the work, they are aware more than anybody else of the overall circumstances at the site at the time of an accident (the composition of activities at the site and their nature, the type of activity, the number of workers involved, equipment in use, organizational conditions, and more).

The result will be a model based on a combination of both conceptual and empirical considerations that will allow determination of the expected level of any risk at any time, based on time-dependent input data for any given construction project. The model enables calculation of the total risk level at any given time, and draws the envelope of the combined risk level (Figure 2).

On the basis of analysis of all the relevant risk factors, a measurement system will be determined. Every hazard will be weighted according to the probability of its occurrence scenarios and the severity of its consequences. The system will be based primarily on the data set collected in the field survey.

The model will be implemented in prototype software that will supply each construction company and its safety managers with information about the fluctuation of various risk levels through a project's duration. The program will utilize the platform of existing construction scheduling software. The scheduled activities and the size of the crews from the scheduling software will provide the input data. By applying the statistical information to the empirical model the program will draw the risk level curves and envelope (Figure 2). The software will be automatically fed from the schedule so that every change in schedule will be interpreted and result in an updated risk envelope.

A LEAN SAFETY MANAGEMENT APPROACH

From a lean point of view, there are three distinct mechanisms through which waste can occur in construction safety programs:

1) Inadequate safety procedures that fail to prevent accidents result in extreme waste and are themselves wasted;
2) Conversely, accident prevention measures that are excessive or inappropriate for the risks present waste resources that could be better applied elsewhere;
3) Safety measures may restrict process flow and reduce productivity.

The time-dependent risk level model can be used to implement management strategies that focus effort where needed and reduce effort where it is wasted. Using a software implementation of the time-dependent risk level model integrated with the scheduling software, managers will be able to predict, analyze and manipulate risk levels along a project's timeline, as indicated in Figure 4. The simplest strategy that exploits improved knowledge of the fluctuation of risk levels is to improve planning of safety enhancement activities; to increase effectiveness and reduce overall effort, as suggested by the 'lean effort' curve of Figure 1.

A more sophisticated strategy, however, is to use the knowledge the model provides, and the model's ability to predict risk levels under alternative planning scenarios, to manipulate a construction schedule in order to lower the peaks in risk level. The initial risk level envelope calculated for a project is likely to include local maxima of accident risk. Local maxima of risk are the result of overlap of activities, each with specific hazards, with interrelated human, business and environmental factor, many of which are time-dependent. Therefore, rescheduling primary

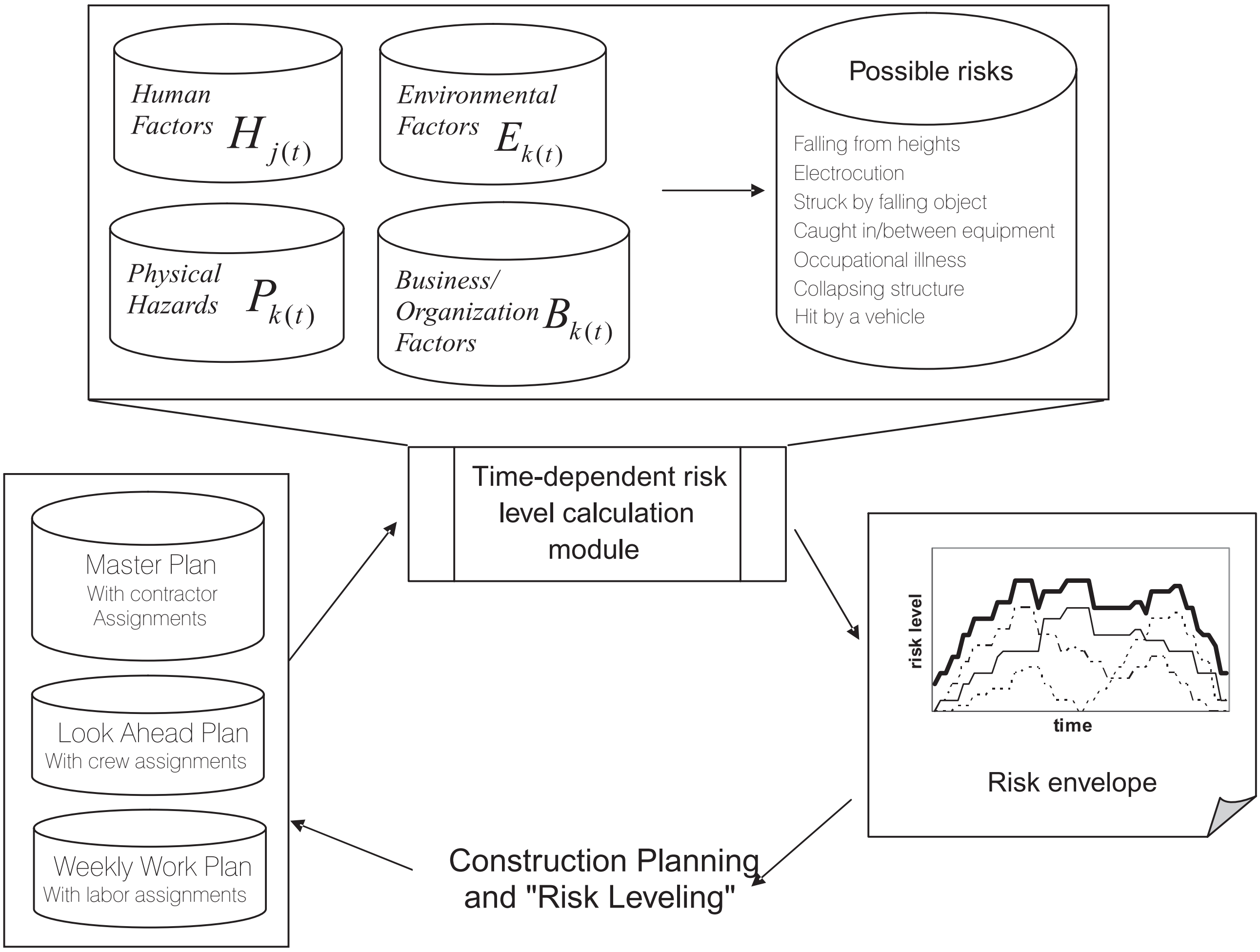

Figure 4: Risk analysis process

construction activities can avoid peaks of risk by removing the simultaneity of activities that led to them. We call this rescheduling 'risk-leveling', which is coined as a paraphrase of the term 'resource-leveling' (management action in adjusting a project schedule to avoid local peaks of resource requirements). Risk-leveling reduces the overall need for safety resources.

According to the Last Planner™ technique (Ballard 2000), there are three levels of planning detail: the Master Plan (the general project schedule) which is usually performed before the work begins, the Look Ahead Plan (planning the work for the next month-two months) which is renewed frequently, and the Weekly Work Plan (assignment of work for the next week). At the first planning level (master plan), management can tackle peaks at the project task level, by changing construction methods, rescheduling major tasks, or planning for safety equipment. The second (look ahead) level can serve company safety supervisors who can now plan how to share their time between all the projects they are responsible for, thus improving their effectiveness. At the most detailed planning level (weekly), project managers and site supervisors can identify the critical risky activities. Here too, they can adjust the daily assignments to avoid local peaks of danger, and/or they are alerted to pay more attention to them. Individual workers with particularly high risk levels can be reassigned to less dangerous tasks.

The third form of waste occurs when a safety measure inhibits a worker (such as protective clothing that restricts movement) or when a safety measure dictated by a certain activity inhibits the ability of other teams to perform unrelated tasks. For example, erection of precast façade panels may restrict access of other workers below the work area. The former must be dealt with at the individual task level, but the latter could be avoided by improved Last Planner™ scheduling, provided the interruptions to process flow can be predicted.

CONCLUSIONS

The degree of risk associated with any potential danger in construction varies through time. Both the probability of occurrence of an accident and the severity of its consequences are dependent on environmental, organizational, commercial, human and technical factors and hazards that vary. Therefore, any occupational safety and health activities that are planned with constant effort are by definition either wasteful and/or ineffective at certain times. They may also restrict project flow unnecessarily.

The time-dependent risk evaluation model proposes prediction of risk levels in construction on the basis of empirical data. An overall risk envelope can be compiled from the time-dependent levels of specific risk types. Ideally, risk envelopes should be calculated at the scope of a company, project, team or individual worker. The goal of the model is to support better planning of accident prevention measures at all levels of detail. Identifying peaks in risk levels enables 'pulling' of prevention efforts to the right people at the right time, rather than 'pushing' generic safety measures to all at less appropriate times. The ability to evaluate risk levels rapidly should also allow planners to proactively reduce peak risk levels by manipulating construction plans, in a procedure called 'risk-leveling'. By leveling the total risk envelope a steady state of safety can be maintained at the site. A more stable level of risk should enable improved safety control and fewer accidents, thus removing one source of instability, and consequently, result in improved work flows.

Although the conceptual model and the implementation strategies have been defined, the challenges of data collection and interpretation, and of software development, remain. Furthermore, the possibility of identifying situations in which safety precautions restrict process flow, and of predicting the magnitude of the impact, has not been explored.

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