Model for Automated Monitoring of Fall Hazards in Building Construction

R. Navon, M.ASCE[1]; and O. Kolton[2]

Abstract: Construction professionals do not attribute to accident prevention the same importance as they do to the main ("value adding") activities. As a result, not enough time and effort are invested in safety issues. Fall from heights ("fall") is the main cause for fatalities and injuries in construction projects. The objective of the present research is to automate fall prevention procedures. An automated model that identifies the dangerous activities in the project's schedule was developed. It also defines the areas in the building where these hazards appear, proposes protective activities (guardrails erection), and integrates them into the schedule. Additionally, it constantly compares the planned guardrails (location and time) and the ones actually used on site. The model provides textual and graphical reports and warns when guardrails are missing, are incomplete, or have been partially removed. The model was implemented, tested in an ongoing project, and presented to 14 experts who were asked to evaluate it. The experts' main conclusions were (1) the model is accurate; (2) the model is a very useful managerial tool in that it identifies all fall hazards, including ones in less visible areas; (3) it enables early detection of fall hazards before and during construction, even during the design stage; and (4) the model is an important managerial, monitoring, and control tool keeping track of all fall hazards and protective measures, and warns when a safety problem occurs.

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CE Database subject headings: Automation; Data collection; Feedback control; Control methods; Hazards; Construction sites; Monitoring.

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Introduction

A third of the accidents in United States construction are caused by falls from height (OSHA 1990, 2002; Hinze et al. 2005) ("fall/s")—the figures in Israel are much higher (close to 60%). The difference can be attributed to the difference in classification methods between the two countries. In both countries falls from heights is, or should be, the most important safety issue in construction—the Israeli Ministry of Labor and Welfare declared this issue the most important safety issue for 2003, which triggered the present research.

The pattern of fall accidents from height are (Hinze et al. 2002) (1) the type of construction (81% of the fall accidents take place at elevations of less than 9.15 m occurring primarily on construction projects of commercial buildings and residential projects of relatively low construction cost); (2) the period of the year (summer); and (3) the day of the week (Monday). In 41% of the falls, workers fell from slabs and roofs, 19% fell from scaffolding and work surfaces, and 11% fell from ladders (Cattledge et al. 1996; Hinze et al. 2002). The writers assert that the availability of protective measures, and controlling them, could have reduced the fall cases, or even eliminated them completely. The present research focuses on the prevention of falls from slabs, roofs and scaffolding (representing 60% of the fall cases).

Standard protective measures include: (1) different types of guardrails—this is the most common and the best measure as it prevents the fall. The model described in the section "Automated Monitoring" below was developed to deal with this measure because it is the most common and the best measure, especially in conventional reinforced concrete construction. All other measures do not prevent the fall, but rather intercept the fallen worker and prevent injury—they include: (2) safety nets, (3) personal measures, (4) protective partitions, or surfaces, and others. These measures are used when guardrails are not feasible as a preventive measure, e.g., when erecting a steel frame.

Guardrails include vertical (posts) and horizontal elements made, mostly, of steel and wood. The rails must sustain 30 kg horizontal and vertical loads to permit safe leaning. The horizontal elements include rails (the top rail at a height of 90–115 cm, and middle one at 65 cm) and toe boards (15 cm height).

Researchers emphasize the importance of safety control as the most important element of accident prevention (Widner 1973; Hinze and Pannullo 1978; Tarrants 1980; Stanton and Willenbrock 1990; Toole 2002). Additionally, the design aspect of the project is a significant contributing factor to site accidents (Gambatese et al. 2005)—hence the writers point out that safety aspects should be considered during the design of the facility. Many factors can cause dangerous situations on site, or accidents. Therefore, to increase safety, the control function has to focus on risk identification and mapping the risk factors on site (Samelson and Levitt 1982; Young 1996; Abdelhamid and Everett 2000). The

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safety control function—planning for safety, monitoring the safety measures, and when needed, taking corrective measures—has to be done in a structured way and has to be based on automated data collection to allow real time warnings to be issued when an unexpected dangerous situation develops.

We have developed a model that monitors guardrails in buildings under construction. The model identifies the activities associated with risk of falling from heights and the areas where these activities are scheduled to be performed. Accordingly, the model plans the protective measures—the guardrails. The model follows up the existing guardrails and constantly compares their locations and lengths to the planned ones. Based on this comparison, the model issues warnings whenever guardrails are missing, or temporarily removed. The model, its implementation, and the onsite experiments are described below.

State-of-Practice Review

A limited field study was conducted to learn more about the specific problems of falling from heights, especially the ones prevailing in Israel. The study was conducted as open interviews among 16 professionals (eight resident engineers, four construction managers, and four foremen) in 12 construction sites (six high rise residential buildings, three high rise office buildings, two hospital extensions, and one service building in the international airport). The participants were carefully selected to cover the relevant professional categories, based on their extensive knowledge and experience. The construction sites were selected to have diversity in the type of buildings in order to maximize the number of problems emerging from the study. The interviews included questions such as: safety management methods; common preventive measures; safety planning and design; as well as the need for the proposed model and the readiness to use it.

Most of the participants did not view safety as an integral part of the construction process. The larger companies normally employ a freelance safety consultant who visits the site twice a month. Hence, she/he does not have time to identify safety hazards ahead of time and plan protective measures, but rather arbitrarily to identify hazards—frequently after they have occurred (up to 2 weeks). Normally, to identify hazards, they ask the foreman which activities are planned in the next few weeks and base their analysis on this information. This means that the hazard identification procedure is not methodological, neither consistent, nor comprehensive. It is not surprising, therefore, that ten out of the 16 professionals experienced fall accidents in their sites (two foremen even experienced it personally). Members of the construction management team are too busy to perform a structured and systematic process of risk identification or plan protective measures. Consequently, it is impossible to monitor and control the safety hazards.

In eight out of the 12 sites we discovered a lack of protective measures for openings in external walls, or at the edge of a slab—in one of the cases we found a reinforced concrete slab of 400 m^2 without guardrails at all, 3 days after it was cast, even though it was the fifth floor. Moreover, even where guardrails existed before, we found that sometimes parts of them were missing.

Automated Monitoring

Principles

The customary methods (e.g., check lists, training, and arbitrary inspection) are insufficient in preventing falls from heights. A more structured and systematic approach is needed. The proposed model identifies activities which expose workers to fall hazards and the areas of work where these activities are scheduled to take place. The model alerts the construction management, in real time, when and where these hazards are not treated by appropriate protective measures: continuous guardrails. To achieve the above, the model does the following:

1. Identifies **activities** associated with fall hazards ("dangerous activities"). These activities are divided into two types: (1) activities that create the hazard—e.g., formwork erection for slabs. A guardrail is needed, hence its installation has to be scheduled, materials have to be ordered, and workers allocated for it. (2) Activities performed in an area with fall hazard—e.g., install rebar, or cast the above slab. In this second case, the model has to ensure that existing guardrails are in place and that they are continuous.
2. Identifies **areas** where fall hazards exist, or an activity associated with a fall hazard is scheduled ("dangerous areas"). These areas are edges of, or openings in, slabs, or openings in external walls. The guardrails are needed in these areas from the time the element erection begins (e.g., beginning the formwork erection) until the hazard is permanently lifted (e.g., after external walls are built on the slab).
3. Recommends protective measures to be taken. The model recommends the exact locations where and the time when guardrails have to be installed or removed and their total length.
4. Warns when guardrails are missing, are incomplete, or have been partially removed for a predefined time. This warning is given as a report, or popup window, and is also represented visually using the building plans modeled in the AutoCAD (Section "Monitoring Model/Output" below).

Three main assumptions are made for the development of this model:

1. The model does not create new norms, but rather it implements existing safety regulations in Israel.
2. The model deals with fall hazards from building elements only—it does not deal with fall hazards from scaffoldings, ladders, or other construction equipment. Moreover, the definition of dangerous activities is currently made based on the type of the activity (e.g., formwork erection, masonry) and the location of the building element. Environmental conditions (e.g., weather, dust, lighting conditions, etc.) are not integrated in the model.
3. The model relies on data from a project model (PM)—an object oriented database which stores, processes and transfers all the data relating to the project at all stages of the construction process (Eastman 1999; Faraj et al. 1999; Han et al. 1999; Tolman et al. 2000; Bjork 2002). It includes uptodate information relating to the physical description of the building, construction planning information, schedule, quantities, and resource-inputs data. The PM is a dynamic database and all the data are updated frequently by automated or manual methods. The structural steel and the precast industries are already relying, or are actively pursuing, the use of such models; hence it is reasonable to assume that these models will be used in major construction projects.

Monitoring Model

Identifying dangerous activities is based on generic databases, which include lists of activity characteristics and others which contain decision rules. The decision on project specific dangerous

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activities is made on the strength of a comparison between the characteristics of the activities in the databases and the ones in the uptodate schedule of the project. Determining dangerous areas is based on the strength of the dangerous activities, the geometric data of the building and decision rules. After identifying the dangerous activities and areas, the model determines where guardrails are actually installed (determined by Module III—section "Monitoring Model/Modules" below) and compares these locations to the planned locations of guardrails (determined by Module II).

Input

The input to the model includes five databases—some are generic, such as the Safety Regulations or Activity Characteristics; and others are project specific, such as the PM, Risk Factors, and Risk Assessment. Some of the databases are dynamic, changing during the operation of the model, either as a result of external events, or stemming from the operation of the model itself. These databases are explained below.

The **project model** provides the monitoring model with important data, such as:

1. Data relating to the building elements—their locations, measurements, and shapes. These data help to determine the location and the length of the guardrails.
2. Schedule related data: list of activities—their start, finish, and duration, and the logical relationship between the activities. These data help to determine when, and for how long, guardrails are needed.
3. The association between the building elements and the activities to construct them. These data are used to link the dangerous activities and building elements.
4. The required inputs needed to construct the guardrails. These data are used to calculate the durations of the guardrail erection activities.

As explained in the subsection "Automated Monitoring/Principles" above, the PM is a dynamic database and all the data in it are, therefore, uptodate. The current model also updates the PM regarding the dangerous activities, the preventive activities, the planned locations of guardrails and the actual locations of existing guardrails.

Risk Factors. This database is needed to define the level of hazard. These factors are determined based on research, or the company's experience—they include: the height the activity is performed at, type of construction, period of the year, day of the week, etc. These are additional factors to the ones defining the risk (see "Safety Regulations" below) which intensify the level of hazard.

Safety Regulations. This database holds the safety regulations relevant to the model. These regulations define the situations considered as dangerous and, hence, require protective measures, e.g., "each employee on walking, or working, surfaces shall be protected from falling through holes, or edges, more than 2 m above lower levels by guardrails systems erected around each dangerous area."

Activity Characteristics. Each activity listed in this database is classified according to predefined characteristics which permit the model to identify it as dangerous (or not), for different construction methods (conventional, industrialized, prefabricated, etc.). These characteristics are:

- Type of activity—e.g., erect formwork, cast, masonry, etc.;

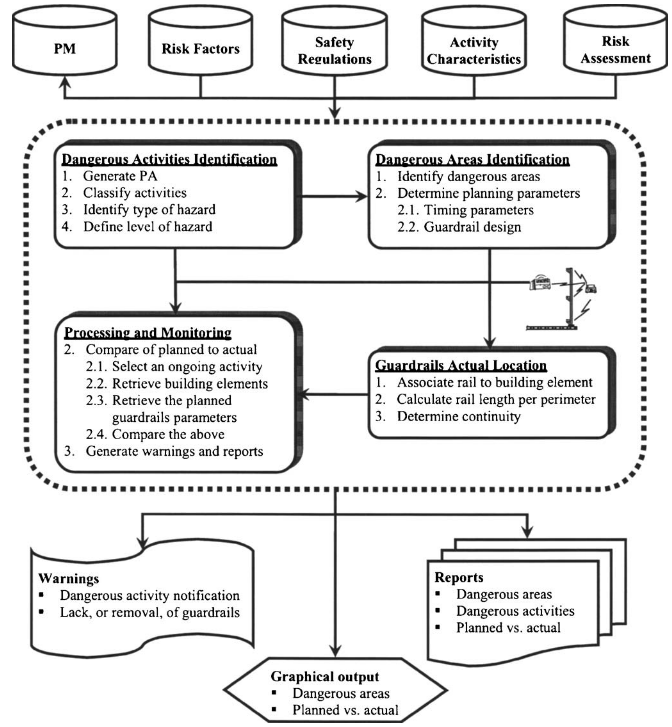

Fig. 1. Schematic model

- The constructed building element—e.g., beam, slab, wall, etc.; and
- The location of the building element—e.g., stair case, roof, elevated slabs, etc.

Each pending activity (see the subsection "Modules" below) is analyzed based on the characteristics in this database and a set of decision rules. The analysis determines if the activity creates a fall hazard, or is performed in an area where a fall hazard exists.

Risk Assessment. This database is built once by the project management team. It includes general characteristics of the project such as the construction method, number of floors, height of a typical floor, and the type of construction (e.g., residential, commercial). These characteristics were identified by Hinze et al. (2002) as patterns of fall from heights. In addition to this, the project management team can optionally mark specific dangerous areas or dangerous activities—this is done by marking specific activities in the scheduling software as dangerous or adding a flag to the AutoCAD drawing to mark a dangerous area.

Modules

The model is divided into four modules: I—a module that identities the dangerous activities, II—another which determines the dangerous areas and designs the guardrails, III—a module that measures the actual location of guardrails, and IV—a module that processes all these data and generates the monitoring information (Fig. 1).

Module I: Dangerous Activities Identification (DAI). The module identifies activities creating fall hazard, or ones performed where a fall hazard exists; classifies them; and identifies the types and the level of the hazards. These activities are generated from a list of pending activities (PA) extracted from the PM. The pending activities are all the activities whose predecessors

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are completed and the ones whose early start falls within a specified time duration (defined by the user). The main steps of the algorithm are:

1. **Generate PA**. The module runs through the activities of the schedule in the PM and retrieves all the ones which answer the conditions for PA as mentioned above.
2. **Classify activities**. The PAs are classified as dangerous (or "not dangerous") by comparing their characteristics to the data in the Activity Characteristics database.
3. **Identify type of hazard**. According to the characteristics of the activity, the module determines if the dangerous activity creates the fall hazard or is performed in an area where such a hazard already exists. The latter type is when the activity has a predecessor that either creates a fall hazard or is, itself, performed in a dangerous area, e.g., install rebar in formwork, the erection of which created the fall hazard. Identifying the type of hazard is done on the strength of data from the Activity Characteristics database and the PM (list of activities).
4. **Define level of hazard**. This step is performed on all the activities classified as dangerous in step 2 above. The objective of this step is to prioritize the dangerous activities so that the attention will be given to the more critical ones. The definition is made based on the combination and the number of the intensifying risk factors (height the activity is performed at, type of construction, period of the year, day of the week, etc.). Defining the hazard level is done using data extracted from the PM and data from the Risk Factors Database.

Module II: Dangerous Areas Identification. The module identifies dangerous areas, determines where and when protective actions have to be taken, and designs the guardrails. The module also produces the data, which serves the generation of the visual (graphical) output for monitoring the guardrails system. The main steps are:

1. **Identify dangerous areas**. The module runs through the list of dangerous activities, received from DAI and, for each, it determines the building elements associated with it. This is done on the strength of the physical design in the PM, the Safety Regulations database, and decision rules.
2. **Determine planning parameters**. The second step is to determine where and when protective measures have to be taken, for how long, and to design the details of the guardrails. Two types of parameters are determined: timing parameters and the physical design of the guardrails: (1) **Timing parameters**. Based on the scheduled time of the dangerous activity and the time it takes to erect the guardrails, the module determines when a guardrail has to be erected and removed. Additionally it determines the type of logical relationship (start-start, finish-start, etc.) between the dangerous activity and the protective activity, based on data in the Activity Characteristics database. (2) **Guardrail design**. For each guardrails-erection activity the module calculates the coordinates and measurement (total length) of the guardrails.

Module III: Guardrails Actual Location. The module dynamically determines where the guardrails are actually installed and whether they are continuous. This is done in order to compare the planned guardrails' locations to the ones actually installed and used, at all times. This dynamic determination is achieved by a technological system that determines the locations, the lengths, and the continuity of the guardrails—a conceptual technological solution for which was developed. The system (Fig. 2) has three components: sensors which determine if the rails are attached to the posts, transmitters, and a central receiver.

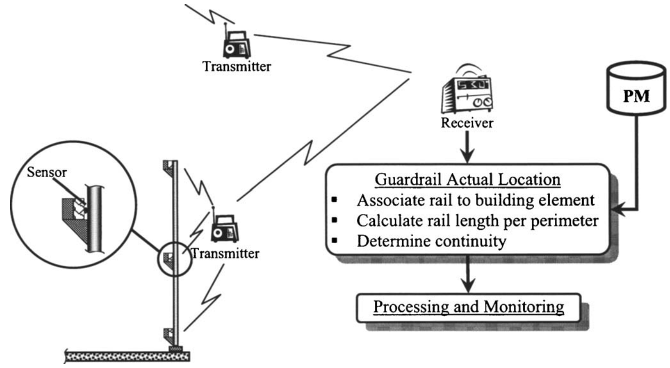

Fig. 2. Guardrail actual location measurement system

The sensors are installed between the post and the rail and they have open, or closed, positions. As long as the rail is attached to the post, the sensor and the electrical circuit are closed. The sensors are wired to the transmitters, which send the status of the sensors to the central receiver. Data regarding each sensor include its status (open or closed), the identification of the sensor, and the identification of the rail. In addition, the transmitter also sends its own identification to enable more precise determination of the locations.

Based on the above data, the module first associates the guardrails with the corresponding building elements. Then, based on additional data provided by the people who installed the guardrails, it calculates the locations and length of the installed guardrails and determines if they are continuous.

Module IV: Processing and Monitoring. The module handles the data processing to generate the reports, and compares the planned timing and location of guardrails to the actual location of currently installed guardrails. It also checks if all the guardrails are continuous and ascertains that none of their elements have been removed.

The comparison between the planned timings and locations of the guardrails and the actual values of these parameters, is carried out for all ongoing dangerous activities and their associated building elements. For each the model performs the following:

1. **Compare planned to actual:** (1) Select an ongoing activity; (2) Retrieve all its associated building elements; (3) Retrieve the planned timings, locations, and lengths of the guardrails from Modules I and II; and (4) Compare with the corresponding parameters of the existing guardrails—the latter taken from Module III.
2. **Generate warnings and reports**—these are described in the subsection "Output" below.

Output

There are three types of outputs: (1) warnings—issued to alert on deviations between planned and actual timings and locations of guardrails; (2) written reports regarding all aspects of fall hazards and the protective measures; and (3) graphical outputs. The latter is used to illustrate the warnings and reports, and as a general means for monitoring and managing fall hazard safety.

The **warnings** include:

1. A notification given before a dangerous activity is performed. The notification can be given in various ways—e.g., a mes-

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sage that pops up when the scheduling software is opened. The user can determine how long before the performance of a dangerous activity she/he wants to be notified. The message window also includes the model's recommended protective measure.

2. A warning when a dangerous activity is performed without an appropriate protective measure. This is done when the model identifies a deviation between the planned timing and locations of the guardrails and the existing ones. This warning is also issued when existing guardrails, or part of them, are temporarily removed (for duration longer than a specified time defined by the user).

It is important that this warning be given in real time so that corrective measures can be taken before it is too late. The model can react in a real time mode due to the fact that Module III checks the status of guardrails and sends data to the model at a high frequency.

All the reports can be given to different time horizons and are also available graphically. The **reports** include:

1. Dangerous areas. The report lists the dangerous areas in terms of time and location for different time horizons, or for various sections of the project. For each dangerous area, it also gives the building element, which terminates the hazard (if applicable), e.g., a concrete slab—the hazard begins after it had been cast and the railing of the formwork, which was part of it, removed with the formwork. This fall hazard terminates once the external walls are built. The report helps the project management team for general risk management of fall hazards.
2. Dangerous activities and protective measures. The report gives the dangerous activities, listing for each its start date and duration. It also gives the activities recommended to erect the guardrails and the recommended logical relationship between this activity and the dangerous activity. It helps the project management team to prepare for the hazard and order materials, labor, and other resources needed to erect the guardrails.
3. Planned versus actual protective measures. This report gives the project management team comprehensive information about the planned guardrails and the ones actually erected. The report details: (1) the exact locations of the guardrails; (2) the date to be installed; (3) the duration that the guardrails will be needed in this location; and (4) their total length in that location. The report also details similar parameters for the guardrails actually erected and compares them to the planned ones.

The **graphical outputs** include:

1. Dangerous areas. This is the parallel output to the report under the same name, but is easier and faster to understand, hence is a more useful management tool.
2. Planned versus actual protective measures. This, too, is the parallel output to the report under the same name. Apart from the warnings, this output shows, at a glance, where guardrails are missing. This output can be viewed anywhere (at the site, or even the main, offices), which makes it a very powerful monitoring tool.

Model Implementation and On Site Experiment

The objective of the implementation was threefold: **first**, the computer program is an important part of any model development as it details the algorithms and checks them. The **second** objective of the prototype, in this case, was to allow the algorithms to be used in an ongoing project ("demonstration project") under real conditions. This added another dimension to the model development since real life situations, using the computerized algorithms, proved to be useful in refining the algorithms. The **third** objective was to demonstrate the model to practitioners and receive their comments so that the model could be improved. The model presented in the section "Automated Monitoring" above is the result of these improvement phases.

In order to achieve the above, the algorithms of the model were implemented in a computer program ("prototype") written in Visual Basic (VB), AutoCAD, and MS Project—the algorithms which identify the dangerous areas and the processing were written in VB. MS Project was used as the database of the uptodate schedule, from which the PA were extracted (at this stage manually) and to write the algorithms that identify the dangerous activities. The data in the MS Project can be filled using standard features such as activity lists, combo boxes, dropdown menus, etc., to allow automated identification of the activities. Another alternative, which was adopted for the prototype, is a hierarchical coding system. AutoCAD was used to model the building, to extract data about the building elements in question—these data were used by the algorithms which identify the dangerous areas. The AutoCAD was also used as a means of visualization for the warnings and reports. At this stage the technological system for the measurement of the actual location of guardrails was not implemented.

The prototype was used in a demonstration project—a nine story apartment building with a total built area of 4,400 m^2 and a total cost of $2,500,000 in Netanya. The experiment checked if the prototype: (1) identifies all the dangerous activities; (2) identifies all the dangerous areas; and (3) recommends the right protective measures—guardrails—at the right times and in the correct locations.

Risk Identification

During the experiment we modeled a section of the demonstration project and used the prototype, which determined the dangerous activities and, for each, it defined the dangerous areas and recommended protective measures.

Dangerous Activities Determination

The coding system of the activities in the schedule was built to enable the identification of their characteristics—these characteristics serve to determine whether an activity creates a fall hazard. As mentioned in the subsection "Input" above, the characteristics relate to the type of the activity, the building element associated with the activity, and the location of the building element. The prototype scans the schedule, using these characteristics, to identify dangerous activities and recommend adding activities to erect the guardrails. The identification is carried out by comparing the characteristics of pending activities to the ones in the Activity Characteristics database. The outcome of the comparison can be one of the following:

1. If all the three characteristics of the activity indicate that the activity is dangerous—e.g., the activity type is "formwork erection," the building element is "slab," and the location is "elevated slab"—the activity is defined as "dangerous." The prototype proceeds by defining what is needed to protect the workers (here the activity "Install Guardrails") and the type of logical relationship between this activity and the other building activities (here "Formwork Erection").

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2. If only one of the characteristics of the activity indicates that the activity is dangerous—e.g., the activity type is "formwork erection," the building element is "foundations," and the location is "underground"—the activity is defined as "not dangerous" and the prototype proceeds to the next pending activity.
3. If the activity has two dangerous characteristics—e.g., the activity type is "formwork erection," the building element is "columns," and the location is "elevated slab"—the prototype cannot always make a unique interpretation (the columns could be internal, or external). In such a case, the prototype issues a query and the user has to determine if the activity is dangerous or not. If the user determines the activity is not dangerous, the prototype proceeds to the next pending activity. Otherwise, if the user determines that the activity is dangerous, the user is also asked if in the future, when activities have the same combination of characteristics, the activity should be automatically defined as dangerous.

Dangerous Areas

For each dangerous activity, the prototype identifies the relevant building element and defines the dangerous areas on the strength of decision rules and data from the Safety Regulations database. This is done by dividing each element into subelements—the algorithm counts the number of "free vertices" of each subelement, which serve as a criterion to determine if the subelement is part of an "open" edge. In the next step, the algorithm checks the height difference between that edge and the surface below it—if the difference exceeds 2 m (which is the requirement by the Israeli code), the algorithm defines the surface as a dangerous area. For these areas, the prototype determines the protective measures, their total length, and the time variables: start date and duration.

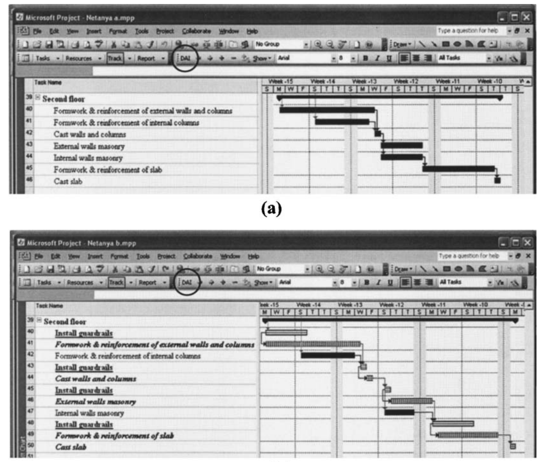
Model Evaluation

The experts' involvement had two main objectives: (1) to accompany the development of the model—Stage I, and (2) to evaluate the model during the on site experiment—Stage II. The survey included 14 participants: five resident engineers, four safety consultants, three foremen, and two academics. Six of the experts participated in Stage I, and eight in Stage II.

Stage I was conducted as an open discussion with each participant separately, in which the principles and the main functions and outputs were presented. The experts were asked to express their opinions about the utility of the model as a managerial and safety management tools. As a result of this stage the model was improved, especially the warnings and the outputs and their format (e.g., the graphical output).

Stage II of the survey was conducted after the prototype was completed. The prototype was used in the demonstration project in parallel to an evaluation of the same project by the experts. The experts were asked to identify the dangerous activities and recommend suitable protective measures. The prototype was run for the same period of time that the experts related to and outputs were generated—the experts were then asked to evaluate the output.

A sample output generated with MS Project, which was used for the experts' evaluation, is shown in Fig. 3. Before running the model, this schedule for the second floor included seven activities [Fig. 3(a)]. After running the model (by pressing the DAI button—circled in the figure) it identified five dangerous activities (it changed the format of the task bar and the font to bold and italics) and proposed protective measures (changed the format of



(b)

Fig. 3. Sample output—Gantt chart including dangerous activities and protective measures

the task bar and inserted the activities in bold and underlined font) and logical relationships with the dangerous activities [Fig. 3(b)]. Table 1 summarizes the activities that the model identified as dangerous, the proposed protective measures and the logical relationships between them. For example, activity number 49 ("Formwork & reinforcement of slab") was identified as dangerous. The model proposed Activity number 48 ("Install guardrails") and inserted it into the schedule with an SS/1 logical relationship. Some of the preventive activities are completed before the dangerous activity commences (e.g., erect guardrails before masonry), in other cases (e.g., slab formwork), the preventive activity can only be performed concurrently with the dangerous one.

The user can review the insertions to the schedule and their overall effect on the schedule and either accept, reject, or change them.

The main conclusions from the comparison between the output of the prototype and the analysis of the experts are:

1. The model is accurate—it identifies the dangerous activities and the locations of the hazard (dangerous areas) and recommends the appropriate protective measures.
2. The integration between the safety components (dangerous activities and the activities to erect the protective measures) and the project's schedule has three advantages: (1) fall hazards can be identified and referred to much earlier than under current practice. This can be done as early as the design stage (Weinstein et al. 2005), during which there is normally no reference to the safety aspects of the construction stage. (2) Identification of hazards that could have been ignored, especially in large projects. (3) The integration permits reference to hazard prevention as one of the activities needed to be

Table 1. Summary of Dangerous Activities and Protective Measures in Fig. 3

Dangerous activity number	Proposed protective activity number	Logical relationship
41	40	SS/0
44	43	SS/1
46	45	SS/1
49, 50	48	SS/1

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carried out during the construction of the project. The equality between the status of the preventive activities and that of the other construction activities increases the weight given to safety issues.

3. The ability of the model to provide risk analysis for selected periods, or defined sections of the work, improves the project management team's ability to prepare itself to prevent accidents.
4. The graphical output is very useful to understand the fall hazards and identify them quickly.

The experts expressed their opinion that the model offers an excellent tool for risk management, which enables a daily monitoring of fall from heights hazards. They emphasized its advantage in introducing a methodological component to safety management on a daily basis, which is a vast improvement to the current practice. As described in the section "State-of-Practice Review" above, safety consultants get to a project twice a month and identifying the hazards is not based on a consistent, methodological, and comprehensive review of all the activities. The experts added that an additional contribution of the model is increased awareness of safety in general, and fall hazards in particular.

Conclusions

Fall hazards represent the highest risk factor in building construction projects—a third of the fatal accidents in the United States, and 60% of them in Israel, are caused by fall from heights. Apart from lack of sufficient awareness to safety in general, and fall from heights specifically, the main reason for this (at least in Israel) is that contractors do not allocate enough resources for accident prevention. This is in spite of the fact that construction accidents are very costly to the contractors (Levitt et al. 1981; Everett and Frank 1996; Son et al. 2000; Burkart 2002; Bobick 2004) the direct and indirect cost can reach above 3% of the projects total cost (Levitt et al. 1981).

An automated model to monitor fall hazards was developed. The model identifies and manages fall hazards among scheduled activities. The model proposes activities, to erect protective measures, which precede the dangerous activity. Additionally, the model identifies the dangerous areas associated with the dangerous activities and presents them graphically on the project's drawings. The model includes a component that continuously monitors the existing protective measures in real time.

The model provides various reports and warnings. The reports are used for planning purposes (e.g., to prepare the materials, or workers, to erect the protective measures). Warnings are given when a dangerous activity is performed without appropriate protective measures, or when the latter were (fully or partially) removed before the dangerous activity was completed.

The model was implemented in a prototype for one type of protective measure (guardrails) and tested on site in an ongoing project. The implementation served to demonstrate and test the model. The prototype was used to analyze fall hazards in the demonstration project, in parallel to an analysis carried out by experts. The results of the two procedures were compared and conclusions were drawn. The conclusions indicated that the model is accurate and useful.

The prototype did not implement two important components of the model: the PM and Module III—the actual location measurement of the guardrails. As mentioned in the subsection "Principles" above, the concept of the PM was tried successfully before—the structural steel and the precast industries are beginning to adopt it. Therefore it is reasonable to assume that such models will be used more routinely in construction projects. The second component—actual location measurement—will have to be implemented and tested in future research. Additionally, the model was focused on conventional construction and on guardrails as a protective measure—different construction methods and other protective measures should also be considered in the future.

The model is a useful managerial and monitoring tool. It is instrumental in identifying the risks of fall from heights, evaluating, and monitoring them. The graphical interface helps in easily determining where these hazards are and aids in focusing on the main problems. The model automatically identifies the hazards, their locations, and the time when they are scheduled to appear, thus almost eliminating the possibility of forgetting to use protective measures (accidents can happen in remote and less visible areas of the project and not only in the main areas). The actual location measurement component of the model adds a control dimension as it compares between the planned protective measures and the ones actually erected on site.

While the proposed model was developed to improve safety during the construction stage, it can be used as a useful tool during the design stage too. By using Module II, the designer can identify dangerous areas and integrate safety measures in the design, e.g., leaving inserts (or holes) in slabs for faster and better installation of guardrails as soon as formwork (with its guardrails) had been stripped.

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