New Method for Measuring the Safety Risk of Construction Activities: Task Demand Assessment

Panagiotis Mitropoulos, Ph.D., A.M.ASCE[1]; and Manoj Namboodiri, M.S.[2]

Abstract: The task demand assessment (TDA) is a new technique for measuring the safety risk of construction activities and analyzing how changes in operation parameters can affect the potential for accidents. TDA is similar to observational ergonomic methods—it does not produce estimates of probabilities of incidents, but it quantifies the "task demand" of actual operations based on characteristics of the activity and independent of the workers' capabilities. The task demand reflects the difficulty to perform the activity safely. It is based on (1) the exposure to a hazard and (2) the presence and level of observable task demand factors—that is, risk factors that can increase the potential for an accident. The paper presents the findings from the initial implementation of TDA and demonstrates its feasibility and applicability on two different operations: a roofing activity and a concrete paving operation. Furthermore, the paving case illustrates how the TDA method can compare different production scenarios and measure the effect of production variables on the accident potential. The findings indicate that the method can be applied on activities of varying complexity and can account for several risks and task demand factors as required by the user. The selection of task demand factors is a key issue for the validity of the method and requires input from the crew and safety management. The limitations of the methodology and the need for further research are discussed. Overall, TDA provides a tool that can assist researchers and practitioners in the analysis and design of construction operations.

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Introduction

Designing operations that are at the same time highly productive and highly safe remains a significant challenge, as indicated by the accident statistics. Productivity analysis methods such as time studies (Oglesby et al. 1989; Howell et al. 1993) and simulation techniques such as CYCLONE (Halpin and Woodhead 1976; Ioannou 1989) and STROBOSCOPE (Martinez and Ioannou 1999) provide the ability to analyze the productivity of an operation, understand the impact of different operational variables and identify changes that improve productivity. However, our ability to analyze or simulate construction activities with regards to safety risks is limited. Currently, there is no methodology that allows researchers and practitioners to measure how the safety risk varies over the duration of the activity and evaluate how the production variables affect the safety risk of the operation.

The long-term goal of this research is to provide methods and techniques to assist in designing productive and safe operations. This requires the ability (and the methodologies) to (1) quantify the safety risk of actual operations and (2) analyze the effect of production variables on the safety risk. Toward this goal, this research developed the task demand assessment (TDA) methodology. This is a new technique developed by the writers for measuring the accident potential of an activity, based on the production variables. The TDA method is based on a cognitive perspective—the premise that the attributes of the task and the environment affect the likelihood of accidents during a construction operation). Methodologically, the method is based on ergonomic assessment methods; it quantifies the task demands due to the risk factors involved in the operation and independent of the workers' abilities and human factors. In addition to quantifying the task demands, this methodology integrates the analysis of productivity with the analysis of safety risk, based on operational variables. The method enables simulation of construction operations and analysis of different operations for both productivity and safety risk.

The paper introduces the method and demonstrates its feasibility and applicability for different activities and risks. For this, the TDA method is used to analyze the safety risk of two cases: a roofing operation and a concrete paving operation. The discussion summarizes the contribution of the method to research and practice and identifies its limitations.

Background

This section reviews current methods to measure the safety risk of an operation and identifies the strengths and limitations of the different methods. Such methods can be grouped in three main categories: (1) a priori risk estimates using expert opinions or statistical data; (2) compliance measures of safe conditions and behaviors; and (3) methods to calculate ergonomic and cognitive

[1]Assistant Professor, Del E. Webb School of Construction, Arizona State Univ., P.O. Box 870204, Tempe, AZ 85287. E-mail: takism@asu.edu

[2]Senior Consultant, Faithful and Gould; formerly, Graduate Research Assistant, Del E. Webb School of Construction, Arizona State Univ.

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demands. Observational methods are reviewed in more detail as they provide the methodological basis for the TDA method.

Risk Estimates

According to the National Safety Council (2009) "risk is a measure of the probability and severity of adverse effects." Methods to quantify the safety risk of construction operations have focused on assessment of the probability (frequency) of incidents and consequences. For example, Brauer (1994) quantified the frequency of event occurrence in subjective levels such as frequent, probable, occasional, remote, and improbable. These methods differ primarily in the approach they use to assess the probability and severity. The two main approaches are based on expert opinions and statistical data.

Several researchers proposed subjective expert assessments to quantify the safety risk. Methods using expert opinions differ in the factors that they take into consideration. For example, Sun et al. (2008) used the analytic hierarchy process and quantified 25 risk factors (e.g., schedule pressure from client) by asking expert participants to rate each component on a subjective Likert scale. Lee and Halpin (2003) developed a fuzzy logic system that uses expert input with regards to three factors: preplanning, training, and supervision. Jannadi and Almishari (2003) used risk scores provided by the user to populate a risk assessor model with severity, probability, and exposure inputs. Yi and Langford (2006) proposed that the risk of an activity depends on the process risk, human resources risk, technology risk, and environment risk. Hallowell and Gambatese (2009) used expert opinion to quantify the probability and consequences of incident events for formwork activities. Everett (1999) analyzed ergonomic risks associated with different construction processes (e.g., install drywall and light gauge steel partitioning) by identifying seven ergonomic risk factors and having experts assess the presence of such factors on a scale of 1 (low) to 3 (high).

Other researchers have used statistical injury data to develop a priori estimates of safety risks. Baradan and Usmen (2006) quantified the risk for various construction trades using data published by the Bureau of Labor Statistics. Wang et al. (2006) estimated the safety risk on projects using the amount of labor hours with the probability and costs (consequences) for different incident types (such as falls, struck by, etc.) which were calculated based on statistical injury data from BLS.

The aforementioned methods provide an a priori estimate of the activity risk. These assessments, however, are independent of how the operation is actually performed. To use a cost control analogy, these systems provide estimates but not actual costs and do not capture or describe the actual safety risk over the duration of the operation. Ways to assess the safety risk of actual/observed operations include compliance metrics and ergonomic methods (which, however, are limited to ergonomic hazards).

Compliance Measurements

Risk assessment is an important part of safety management. In construction a typical approach to risk assessment consists of hazard identification before the activity, such as job hazard analysis and identification of the safety measures needed. Evaluations of workplace safety have focused primarily on observations of unsafe conditions and behaviors. Such methods typically measure the frequency (percent) of safe-unsafe behaviors or conditions. Such metrics are also used in behavior based safety (Krause 1997; Geller 2005). Such assessments are independent of operational variables as they do not account for the production factors that increase the unsafe behaviors.

Ergonomic Assessment Methods

Several ergonomic methods have been developed to evaluate the potential for musculoskeletal disorders (MSDs) based on characteristics of the operation. Such methods evaluate the physical demands on workers based on specific characteristics of the activity (physical loads, posture, etc.). These methods do not calculate the likelihood of injuries (as this depends on many other factors), but assess the ergonomic task demands, which create the potential for injury. Depending on the data collected, ergonomic assessment methods are of three types: (1) self-reports; (2) physiological measurements; and (3) observational methods (Li and Buckle 1999; David 2005).

Self-reports from workers can be used to collect data on workplace exposure to both physical and psychosocial factors by using methods that include worker diaries, interviews, and questionnaires. *Physiological* measurements using monitoring instruments that rely on sensors attached directly to the subject for the measurement of exposure variables at work (David 2005). Such as heart rate elevations, percentage of available heart range rate, oxygen consumption, electromyography, etc. (Abdelhamid and Everett 2002; Bernold et al. 2001; Saurin and Guimarães 2006; Chang et al. 2009).

Observational methods calculate the ergonomic demand based on observation of key ergonomic risk factors for different body parts. Observational methods vary in terms of complexity (David 2005) and the risk factors they account for. The main risk factors related to MSDs are the load, the posture, and the frequency, but others are often accounted for such as task duration, vibration, etc.

Observational methods include the Ovako working-posture analysis system (OWAS) (Karhu et al. 1977), the cube model (Kadefors 1994, 1997; Sperling et al. 1993; Rwamamara 2007), Ergo-SAM (Laring et al. 2002; Christmansson et al. 2000), and the quick exposure check (QEC) (David et al. 2008). OWAS is a work-sampling technique that enables an observer to assess and record data on a number of factors using specifically designed proforma sheets. OWAS evaluates the ergonomic workload of different body parts, based on the posture and load. Buchholz et al. (1996) developed a modified OWAS for construction called PATH (posture, activity, tools, and handling) as a work sampling method to evaluate ergonomic risk factors.

The cube model calculates ergonomic demand based on the assessment of three risk factors: (1) the force that a worker exerts; (2) the work posture; and (3) the frequency of the force exertion. Criteria are formulated to identify in operative terms what constitutes low, moderate, and high demands for each factor. The model assigns a score of 1 for low demand, 2 for moderate, and 3 for high demand. The overall ergonomic demand is calculated as the product of the three scores: Total demand $=$ force $\times$ posture $\times$ frequency—the score can range from 1 to 27. The demand is considered acceptable if less than 5, conditionally acceptable if between 5 and 10 and unacceptable if greater than 10. Ergo-SAM is a more recent methodology based on the cube model developed to assist industrial production engineers predict the ergonomic demands of production activities at the design stage of the production (Laring et al. 2002). QEC was developed in the U.K. and

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calculates the ergonomic demands as a combination of the above three factors, as well as additional factors such as vibration and duration (David et al. 2008).

Cognitive Assessment Methods

In cognitive systems engineering, techniques have been developed to assess the mental load on operators working with human-machine systems. Four techniques are commonly used to assess mental workload: physiological measures, subjective rating measures, primary task performance measures, and secondary task measures (Meshkati and Loewenthal 1988). The most widely used techniques use subjective workload assessments. Subjective mental workload is defined as the subject's direct estimate or comparative judgment of the mental or cognitive workload experienced at a given moment (Reid and Nygren 1988). Such techniques are the National Aeronautics and Space Administration task load index (Hart and Staveland 1988) and the subjective workload assessment technique (Reid and Nygren 1988). Even though much effort has been made to develop objective measures of workload, subjective workload assessment techniques continue to be popular due to their ease of use, general nonintrusiveness, low cost, high face validity, and known sensitivity to workload variations (Reid and Nygren 1988).

Limitations of Risk Assessment Methods

In summary, the existing methods for assessing safety risk can provide a priori risk estimates and can measure the frequency of unsafe behaviors or conditions. These techniques do not provide a way to assess the potential for accidents based on the actual execution of the operation. Ergonomic methods provide this capability but only for ergonomic hazards, and not for traumatic injury incidents, such as falls, struck by, etc. To address this limitation, this research develops the TDA methodology.

Task Demands Assessment Methodology

Background

The TDA methodology is a new technique developed by the writers in order to analyze the effect of production variables on the accident potential of an activity (Namboodiri 2007). This was needed in order to analyze construction operations for both productivity and safety. With regards to productivity, time studies (Oglesby et al. 1989) were used to analyze an operation and identify changes to improve productivity. However, there was no specific methodology to indicate if the accident potential of the operation changed. Thus, the goal of the initial study was to develop an analytical method to quantify the activity risk and compare similar operations with regards to their accident potential.

The methodology was developed based on observation and analysis of three concrete operations: (1) a concrete paving operation; (2) a formwork operation for concrete diaphragm walls on a bridge; and (3) formwork operation (Namboodiri 2007). Later, the method was used to analyze the safety risk of other activities—roofing, framing, etc. The paper reports the results from the early use of the TDA method—the results identify the strengths and limitations of the methodology and indicate directions for further research.

Theoretical Foundation

The TDA methodology has two key points of departure: (1) with regards to methodology, TDA is based on observational methods for ergonomic assessment reviewed in the previous section and (2) theoretically, TDA is based on the task demand-capability model for construction safety (Mitropoulos et al. 2009). According to that model, when a worker is exposed to a hazard, the likelihood of incidents depends on the task demands and applied capabilities—it increases when task demands increase and reduces when applied capability increases. As shown in Fig. 1, task demands depend on factors related to the task (support conditions, tools, loads, etc.) the environment (other activities, weather conditions), and worker's behaviors (postures, etc.). The applied capability depends on the worker's skill and capability, human factors (such as fatigue, etc.) and the level of activation. The purpose of the TDA method is to develop an objective assessment of the task demands with regards to specific hazards, independent of the workers' applied capability.

Key Characteristics

With regards to scope, this method focuses on traumatic injuries and does not capture the risks arising from overexertion injuries, physical fatigue, and/or occupational illnesses. Its main purpose is to be used for detailed analysis of activities in the same way that time studies are used to analyze/improve productivity, and ergonomic studies are used to analyze/reducing ergonomic loads. The TDA method has the following key characteristics: it is an *observational method* that provides an *objective assessment* of an activity's *task demand* based on observable risk factors. First, TDA provides an assessment of an activity's *task demand* based on observable risk factors. The method *does not* provide estimates of safety risk in terms of probabilities and consequences. It quantifies the task demand—that is, the difficulty to do the work safely based on observable risk factors of the specific operation. Second, it is an *observational method* that enables detailed analysis of an activity. Based on observation/videotaping of the operation, it calculates the accident potential over the duration of the activity for the risks examined, thus producing a "risk profile" of the actual activity. Third, TDA is an *objective assessment* (as opposed to a subjective assessment) because it quantifies the potential for accident independent of the capabilities of the worker performing the task.

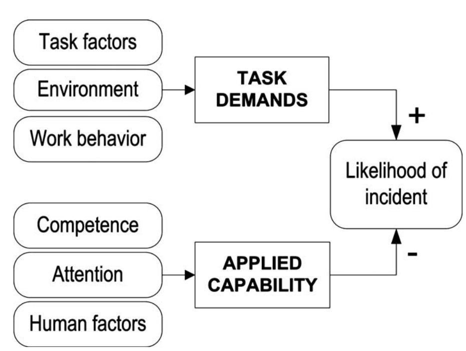

Fig. 1. Task demand-capability model of construction safety (adapted from Mitropoulos et al. 2009)

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Analysis Steps

To calculate the task demands the TDA method involves the following steps.

Understand the Operation

Interviews with supervisors and crews develop an understanding of the operation—the layout, estimated productivity, crew composition, preparation, work distribution and tasks, coordination needs, risks and hazards, etc.

Identify the High Consequence Incidents and Hazards

Ergonomic methods analyze the ergonomic demands separately for different ergonomic incidents—back, shoulders, etc. In a similar way, the TDA analyzes the task demand separately for different potential incidents. For example "fall from elevation" is the potential incident; the unprotected edge is the physical hazard. In the cases used to develop the method, the researchers focused on the incident events with the highest severity potential. These are the potential injuries with the highest cost (individual suffering and claims cost for the organization). These potential incidents are identified through review of the task hazard analysis performed by crew, and discussions with the supervisor and crew about what they consider the most significant risks.

Identify the Conditions of Exposure

The exposure to a hazard is calculated as the percentage of the time that a worker is exposed to the relevant hazard. The percentage of time is used to normalize and compare different operations, and is consistent with measurements in ergonomics methods. For each hazard, the analyst and practitioners need to define what conditions constitute "exposure to the hazard." This can be based on relevant regulations—for example, workers were considered exposed to a fall hazard if they were less than 6 ft away from an elevated edge or opening. The exposure conditions must be observable and unambiguous (for example, 6 ft from the edge), so that it does not depend on the observer's judgment. Safety measures often reduce exposure to hazards; for example, fall arrest equipment protects workers from falls. The TDA method can measure the accident potential with or without the safety measures used—for example, with regards to the fall from elevation hazard, the method can calculate the exposure of a worker to heights above 6 ft, with or without the use of fall arrest equipment.

Identify Task Demand Factors and Values

The potential for accident depends on the presence and level of risk factors (task demand factors) that relate to each risk examined. A central issue in the TDA method is the identification of the risk factors that determine the task demand. In ergonomics the three primary risk factors for MSDs are force, work posture, and frequency. However, with regards to traumatic injuries (falls, struck by, etc.) there is no established framework of risk factors. The risk factors depend on the hazard examined and the operation; in the TDA method, these factors are determined by observing and analyzing the operation and interviewing the activity participants. For example, for a roofing activity the primary risk is fall from elevation and risk factors related to falls include the roof slope, worker's movement, etc.

In the TDA method each task demand factor is assigned a value of low, moderate or high. The numerical values used are 1 for low, 3 for moderate and 9 for high. This approach is similar to the cube model and other ergonomic methods. In order to assess the task demand, the analyst needs to specify the operative criteria that determine if a task demand is low, moderate, or high. For example, if a task demand factor is "distance from the unprotected edge," the task demand values may be "high" if the distance is less than 6 ft, moderate if the distance is between 6 and 10 ft, and low if the distance is greater than 10 ft. Such conditions need to be specified in an unambiguous way, to minimize observer bias. The criteria for low, moderate and high task demand should be developed with input from the work crew.

Calculate the Task Demand

Once the exposure and task demand factors have been defined, the analyst reviews the video of the operation and records how the task demand values for each factor change over time. This produces a graph that indicates the level of task demand over time for each task demand factor. When there are more than one task demand factors, the overall task demand is calculated as the sum of the individual task demands. The accidents potential for a particular hazard is calculated as the task demand level multiplied by the percent of exposure time. For example, if 50% of the time the task demand is low (1), 30% of the time it is moderate (3) and 20% of the time it is high (9), the overall task demand would be $0.50 \times 1 + 0.30 \times 3 + 0.20 \times 9 = 3.2$. This reflects the average task demand during the activity.

The two case studies that follow illustrate how TDA quantifies the safety risk for different activities and risks. The paving case also illustrates how TDA can analyze different production scenarios and compare them with regards to productivity and safety risk.

Roofing Operation

This case study analyzes the accident potential of a residential roofing activity. The activity is the installation of three 10-ft units of flashing, by two workers on a two story house with roof slope greater than 5:12. The activity involved three tasks: transporting the material, preparing the material for installation by shaping them for easier positioning, and installing them by nailing them at the eave. The duration of the three cycles was 4 min and 10 s.

Identify Key Hazards

The primary risk in the roofing operation is fall from elevation.

Determine Exposure Conditions

The roofers were considered exposed to the fall hazard the entire time they were on the roof. The crew did not use any perimeter protection or fall arrest equipment (these measures are not required in residential construction operations).

Identify Task Demand Factors

Discussions with the crew identified three main task demand factors that affect the difficulty of performing the work safely: (1) roof slope; (2) distance from the edge; and (3) workers' movement. Table 1 summarizes the conditions that affect the level of task demand for each factor.

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Table 1. Task Demand Factors and Conditions Determining Level of Task Demands

Task demand factor	Task demand level		
	Low (value=1)	Moderate (value=3)	High (value=9)
Roof slope	No slope	Slope ≤ 5:12	Slope ≥ 5:12
Distance from edge	At ridge	More than 6 ft from edge	Less than 6 ft from edge
Body movement	Stationary	Moving forward	Moving backward

Calculate Accident Potential

Using the video of the activity, the task demand level for each factor was identified for the duration of the work. Fig. 2 illustrates the task demand factors and the cumulative task demand for one worker. The combined task demand is a sum of the individual task demand factors. The method provides a way to capture and quantify the presence and level of task demands factors, and the task demand score reflects the overall level of difficulty.

Concrete Paving Operation

This case study analyzes a concrete paving operation. The analysis first examines the productivity and safety risk of the observed operation. Then it analyzes the productivity and accident potential for different production variables in order to identify the effect of production changes on accident potential and productivity.

The project involved upgrading of airport taxiways from asphalt concrete to Portland cement concrete pavement. The operation studied was the paving of one section performed in one night shift 8 h long. The section was 300–350 ft long, 37.5 ft wide by 19.5 in. deep and lied between two paved sections. The concrete was supplied by a batching plant at the airport and was delivered to the paving area by eight trucks. The paving operation involved three distinct activities: (1) placing the concrete in front of the paver; (2) paving; and (3) concrete finishing behind the paver. The three activities needed to stay relatively close to each other, so that the speed of the paver and the workability of the concrete were not affected.

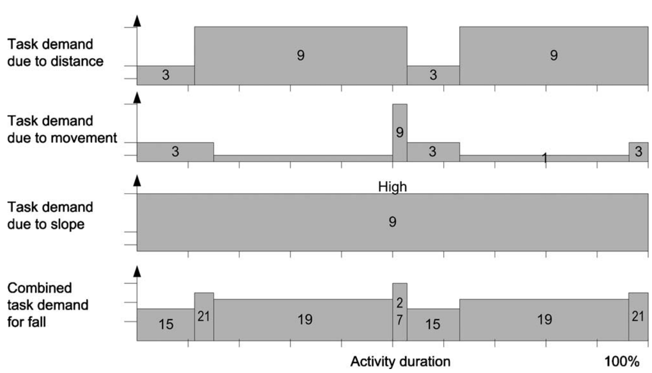

Fig. 2. Task demands for roofing activity

Fig. 3 illustrates the layout of the operation and the crew involved. The section was divided in two lanes where the trucks backed up and dumped the concrete. The concrete delivery rate was one truck every 2.5 min at each lane. Each truck load provided concrete for approximately 4 ft in front of the paver in each lane. During the operation, the paver reached and maintained a speed of 1 ft per minute. The paving crew consisted of 10 workers (not counting the superintendent, the paver operator, and the mechanical foreman). The general foreman supervised the entire crew and was in constant communication with the batching plant.

Placing the Concrete in Front of the Paver

The two laborers and the superintendent performed the following tasks: (1) the laborers guided the trucks as they back up to the right location, opened the truck gate, and guided the truck to dump the concrete. The cycle time of dumping the concrete varied from 52 to 72 s (62 s on average). Each laborer was assigned one lane in which to guide the trucks; (2) set the dowel baskets every 8 ft (which is every two trucks for each side). It took two people to move the dowel baskets in place; if the other laborer was busy guiding a truck, the first laborer had to wait or the superintendent was helping. After setting the dowel baskets, one laborer fixed the dowel basket onto the ground with a nail gun. Setting the baskets took 14 s on average and fixing the baskets took 60 s.

The superintendent supervised this activity. His primary concern was to maintain the smooth and continuous delivery of concrete so that the paver, once started, did not stop. Another

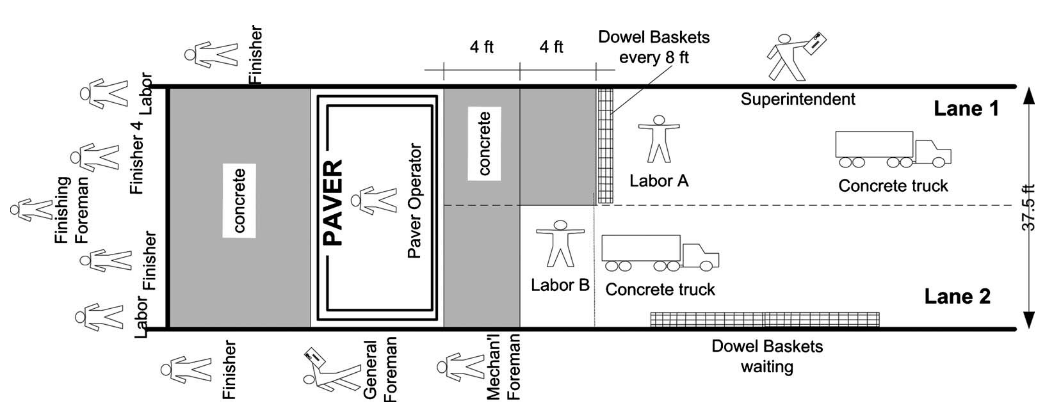

Fig. 3. Layout of paving operation

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important concern was to support the laborers in front of the paver—the superintendent sometimes helped guide the trucks and place dowel baskets.

Paving

The speed of the paver was 1 ft per minute. The paver operator took instructions from the superintendent regarding the speed of the paver.

Finishing behind the Paver

The finishing crew vibrated and finished the concrete. The crew included four finishers, two laborers, and a finishing foreman who performed the following tasks: vibrated and troweled the concrete, checked paver alignment and concrete edge, checked the concrete surface, and added or removed excess concrete.

Productivity and Safety Analysis

Because of the linear nature of the project the productivity in this case was expressed in linear feet of section paved per minute. Thus, the productivity of the operation was indicated by the speed of the paver, which was 1 ft per minute. The TDA included the following steps.

Identify Key Risks

Before the operation the superintendent, foreman, and crew performed a task hazard analysis and discussed safety issues. The most significant injury risks were identified in the activity "placing concrete": (1) getting hit by the moving truck and (2) getting hit by the paver. Thus, the analysis focused these two potential incidents and the two laborers in front of the paver.

Determine Exposure Conditions

For the hazard "hit by paver," it was considered that exposure exists when the worker is less than 6 ft from the paver. Because only a portion of the operation was videotaped (about 30 min which also included the finishing), the workers' actual positions were not recorded throughout the operation. The observations indicated that in general, the workers were standing near the end of the concrete buffer. This was always the case when the workers were guiding the trucks; for the rest of the time it is a conservative estimate. Hence, this assumption was used for the analysis. The length of concrete in front of the paver was calculated based on the truck arrival rate and the paver's speed; each truck added 4 ft of concrete, and every minute the concrete was reduced by 1 ft. For the hazard "hit by truck," the exposure to the hazard starts from the moment when the truck starts backing up, to the point when the truck leaves. The rest of the time, the workers are not exposed to this hazard.

Determine the Task Demand Factors

For the hazard hit by paver, it was considered that the task demand depends on the distance between the worker and the paver—the smaller the distance, the greater the task demand. If the distance was between 4–6 ft, the task demand was considered low, between 2–4 ft moderate, and less than 2 ft high. For the hazard hit by truck, the task demand was determined as follows, based on observations of the operation and discussion with the superintendent. When a laborer guided the truck, the worker's full attention was at the truck and the worker and the driver were in direct communication. In this case, the task demand was considered low (1). If the truck was backing up while the laborer was performing another task behind the truck (setting the dowel baskets) and the superintendent was monitoring the truck, then the task demand was considered moderate (3). In two instances the superintendent stopped the truck until the laborer finished. Finally, if the truck was backing up while the laborer was behind the truck performing another task and no one else was monitoring the truck, then the task demand was considered high (9).

Calculate the Task Demand

Fig. 4 shows the task demand charts for Laborer B. The analysis uses the average task durations. Truck arrives in each lane every 2.5 min. In the analysis, the truck waits for the laborer to guide it; hence, the task demand for hit by truck is always low. The task demand for hit by paver depends on the workers distance from the paver.

As shown in Fig. 4, the demands for both hazards may increase simultaneously; for example, in minute 4:00–5:00, the worker is very close to the paver while at the same time the truck is backing up. The combined presence of task demand factors may further increase the task demand; while the attention of the

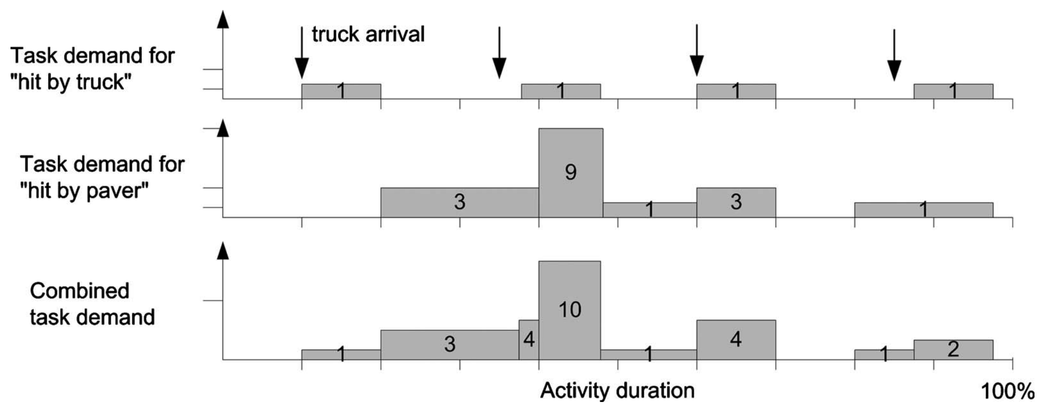

Fig. 4. Task demands for Laborer B

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Table 2. Task Demand for Each Hazard and Worker

Worker	Risk: Hit by truck	Hit by paver	Combined
Laborer A	40%×1=0.40	25%×1+25%×3=1.000	1.40
Laborer B	40%×1=0.40	30%×1+30%×3+7.5%×9=1.875	2.275
Total	0.80	2.875	3.675

worker is on the truck, this may increase the risk of hit by paver. Table 2 summarizes the overall task demand for each hazard and laborer.

Analysis of Alternative Scenarios

The TDA method can be used to analyze how changes in the production variables (paver speed, truck arrival, and work rules) would affect productivity and safety. To illustrate this, the task demand was calculated for three different production scenarios as shown in Table 3. In each scenario, the differences in paver speed and truck arrival resulted in different task demands.

Scenario 2 indicates increased risk of hit by paver because the greater speed of the paver results in a smaller concrete buffer. In Scenario 3, trucks arrive more frequently, hence the safety risk increased due to increased exposure to trucks. Often the trucks arrive while the laborers are setting or fixing the dowel baskets. However, the trucks wait for the worker to guide them to position. Thus, the task demands due to trucks did not increase (the task demand value remained 1). In Scenario 4, the trucks do not wait for the workers to guide them. As a result, there is increased risk as the trucks back up while the laborers are fixing the dowel baskets. In the actual operation, this problem is addressed organizationally, having the superintendent watch out for the laborers as an important part of his functions. This element was not included in Scenario 3b, but it could be easily addressed in another scenario. Fig. 5 summarizes the productivity (paver speed) and accident potential of the scenarios analyzed.

Discussion

The TDA methodology provides a new way to measure the safety risk of construction activities. However, the method does not estimate the safety risk in terms of probability and consequences, but it quantifies an activity's safety difficulty (task demand) based on characteristics of the task. In a way parallel to ergonomic methods, it measures the task demand based on the exposure and level of risk factors, and independent of the workers capability.

Flexibility

The TDA method can be used for different activities and risks. A key element of the methodology is the identification of the risk factors affecting the task demand for each hazard. Because each activity analyzed may involve different hazards and risk factors, these factors are not predetermined (as in the ergonomic methods), but need to be identified in every case. The number of hazards and task demand factors that need to be considered depends on the complexity of the activity analyzed. However, the basic method remains the same independent of the number of factors considered.

Comprehensiveness

In terms of comprehensiveness, that is the task demand factors taken into consideration, the method allows a great degree of flexibility to the user to analyze as many hazards and factors as needed.

Validity

The validity of the method depends largely on the selection of the task demand factors. This should be done with input from the production and safety personnel as this will assure that the important factors are accounted for, and will ensure the validity of the analysis. Furthermore, establishing objective criteria for low, moderate, and high demand values reduces observer's bias.

Similar to ergonomics methods, validation of the TDA results is a challenge. Ideally, the validation of the method would require comparison of the results with an accepted way to measure the task difficulty. Currently, however, there is no other objective metric of task demand for traumatic injury risks. Thus, the main alternative is to use the subjective assessment of the workers who experience the task demands. For this, it is important to use the crew's input with regards to the task demands factors.

Contribution to Operations Improvement

The TDA method provides a systematic approach for identifying interventions and safety improvements. First, it clearly identifies

Table 3. Scenarios Analyzed and Summary of Results

Scenario	Paver speed (ft/min)	Truck arrival per side (min)	Who guides truck	Safety risk "truck"	Safety risk "paver"	Combined task demand
Actual case	1.0	2.5	Worker	0.80	2.875	3.675
Scenario 2	1.5	2.5	Worker	0.80	6.100	6.900
Scenario 3	1.5	2.0	Worker	1.00	3.850	4.850
Scenario 4	1.5	2.0	No one	2.20	2.875	5.075

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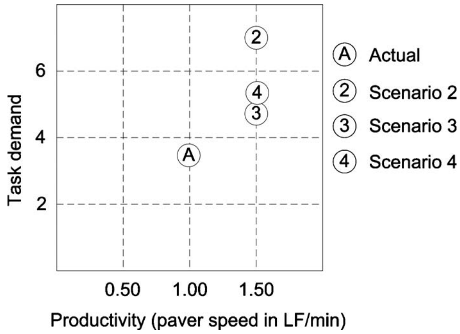

Fig. 5. Productivity and task demands for the scenarios examined

conditions of exposure and the task demand factors. This creates a deeper understanding of the operation, the key safety variables and potential trade-offs between productivity and safety. Second, it increases understanding of the aspects of the operation that can reduce the exposure to or the level of the task demand factors. This guides safety improvements efforts toward changes in the work that (1) reduce exposures and/or (2) reduce the level of task demands. Third, it provides a tool to evaluate and compare the accident potential of alternative production designs as the paving case illustrated. The method provides a way to capture and quantify the presence and level of task demands factors and the task demand score reflects the overall level of "safety difficulty" for the specific operation parameters. The score is not meant to be an accurate measure of task demand.

Implementation

The TDA method can be used by contractors to analyze selected operations or to compare different production scenarios, in the same way they use time studies for productivity analysis or ergonomic studies. The method is not expected to be used for continuous monitoring of operations. Despite the variability and dynamism of construction activities, the practical value of the TDA method is the identification of and attention to the underlying task demand factors. However, if the work method or situation changes in a way that new significant task demand factors are present, then the activity will have to be analyzed again.

The primary users will by the individuals or groups in the contractor's organization who perform the productivity improvement or ergonomic studies (such as internal analysts or safety professionals) or external consultants. Implementation will require some basic training in the method, and the time to videotape the operation and perform the analysis.

The methodology has the following limitations and areas of difficulty:

- Scope. As discussed earlier, this method focuses on traumatic injuries and does not capture the risks arising from overexertion injuries, physical fatigue, and/or occupational illnesses.
- Task demand values versus probabilities. As discussed, the TDA method does not estimate the probability that an incident will occur, but provides a measure of an activity's accident potential based on task demand factors. The method does not correlate the task demand values with probability of incidents. This is beyond the scope of the methodology. Furthermore, the extent to which each factor contributes to the probability of incidents is also beyond the scope of the methodology and subject of future safety research. Even with this limitation the methodology can be used to compare the accident potential between different designs of the same operations and evaluate how changes in the activity can reduce the accident potential.
- Effect of multiple task demand factors. The effect of multiple task demand factors is captured by adding the task demand values. However, the extent to which the difficulty increases with the combination of risk demand is beyond the scope of the TDA method and subject of further safety research.
- Effect of multiple hazards. Similarly, the presence of multiple hazards may also increase the likelihood of incidents, as the workers may have to divide their attention (which is a limited resource) to the task and the multiple hazards. The effect of combined hazards on the safety risk needs to be further investigated, as the safety risk may increase disproportionately when two or more task demand factors occur simultaneously.
- Task demand metric. The calculation of the overall task demand reflects the average task demand over the duration of the activity. Another metric for the accident potential is the frequency of unacceptable task demand levels, that is, the percent of time that the task demand exceeds some limit of acceptability. For example, in the cube method, for the three ergonomic risk factors (load, posture, and frequency), the demand can range from 1 to 27 and the acceptable level is set at 5. The level of acceptability would have to be determined by the management and the crew. The value of the methodology is that it brings all these safety issues into focus.

Despite the limitations, the TDA methodology provides a useful tool that researchers and practitioners can use to measure and improve both the productivity and safety of construction operations. The TDA method provides researchers and practitioners with a tool for analyzing the accident potential of different production designs and identifies how changes in the operation affect the accident potential. This ability will facilitate the design of safer and more productive operations.

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