Case Study

Assessment of the Productivity of Nighttime Asphalt Paving Operations

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Abstract: Performing highway construction operations during nighttime hours has emerged as a response to traffic congestions caused by daytime lane closures. Work zone conditions at night may be different from those during the day, and nighttime factors that affect project metrics (i.e., safety, quality, and productivity) should be carefully considered during the planning of nighttime projects. Currently, there is no methodology for quantifying the effects of nighttime factors on the productivity of construction operations. The objective of this study therefore is to create such a methodology, specifically for asphalt paving projects, focusing on visibility, personnel fatigue, and glare. The methodology is demonstrated using an example case. First, nighttime qualitative (subjective) factors affecting the productivity of asphalt paving operations are identified. A productivity index (PI) is then estimated to account for these factors. The PI value is subsequently used to modify the baseline productivity simulated by a discrete event model of a paving operation, and is then compared with the actual productivity of the case study project. The analysis indicates that the productivity of the asphalt paving operation in the case study can be predicted within an acceptable accuracy range, implying that the calculated nighttime PI can adequately capture the effects of nighttime factors. Quantification of the effects of nighttime factors could help practitioners understand the extent of these effects on their projects. Because nighttime operations are usually more expensive—attributable to overtime payments, night premium payments, lighting expenses, and costs associated with enhanced traffic control—a better estimate of productivity during the early stages of the project, and accounting for the effects of nighttime factors, could lead to better planning and result in cost savings. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000531.

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Introduction

There is an increasing trend towards nighttime highway construction and maintenance operations as a result of traffic congestion and the associated social costs related to daytime highway projects. For instance, to reduce the congestion attributable to daytime projects, during the peak summer roadwork season of 2001, 22% of highway construction and maintenance projects in the U.S. were performed at night, and 18% of those were performed all day and nearly all night (more than 18 h/day) (FHWA 2008). Different work zone conditions (e.g., incoming traffic glare, visual difficulties, and visibility issues) that are present during nighttime hours relative to daytime operations may affect safety, quality, and productivity, which are the significant project metrics in nighttime operations (Hancher and Taylor 2001; Al-Kaisy and Nassar 2009). Of considerable concern in nighttime operations is decreased productivity, which affects the project schedule and cost because nighttime projects are usually more expensive, itself attributable to overtime payments, night premium payments, lighting expenses, and costs associated with enhanced traffic control. A few research studies aimed at assessing productivity in nighttime highway construction projects have been conducted, but no framework has been developed to quantify the effects of nighttime factors on the productivity of an operation. If the effects of nighttime factors are not incorporated in the productivity estimation of construction operations, the estimate will fail to provide accurate information for planning purposes.

The objective of this study is to create a methodology that allows for such a quantification and, therefore, a better understanding of the effects of the qualitative nighttime factors that cause disruptions in the productivity of asphalt paving operations. Such factors as fatigue and visual difficulties affect the operation's productivity but are difficult to quantify. The components of the proposed methodology are shown in Fig. 1. These components include: (1) a discrete event simulation to facilitate analysis of the baseline productivity of the operation while incorporating the effects of reduced equipment speeds and (2) a qualitative factor worth (QFW) model to facilitate consideration of disruptions, both of which are attributable to nighttime factors. As shown in Fig. 1, the data required for creation of the discrete event simulation include the equipment speeds and lead times between different tasks, and these data were obtained from site visits. The effectiveness values and weights of nighttime factors affecting productivity were provided by project personnel, and were used to calculate the productivity index (PI). This in turn was used to modify the baseline productivity estimated from the discrete event simulation. Unlike previous

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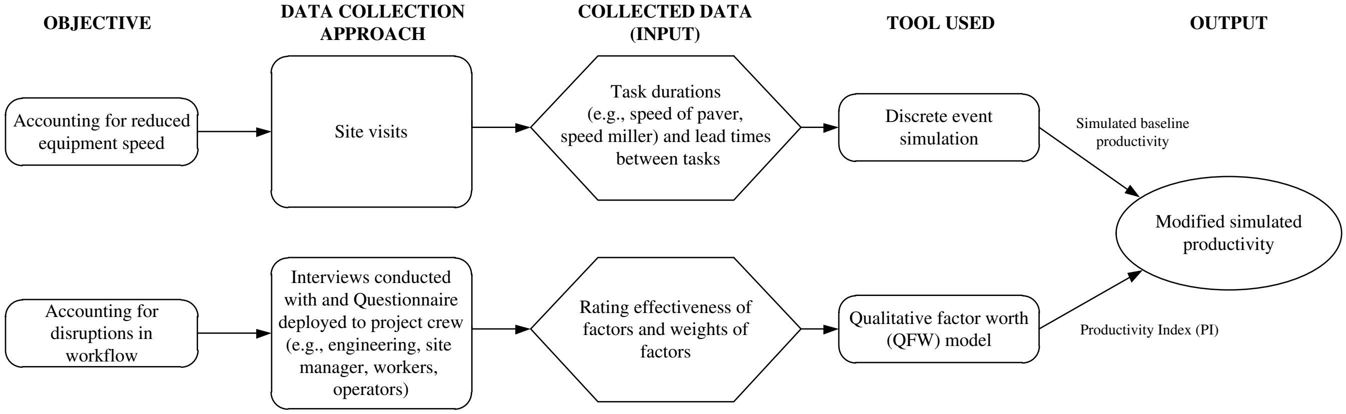


Fig. 1. Components of the proposed methodology

studies related to the assessment of the productivity of nighttime construction operations, the methodology proposed in this paper provides an approach for the quantification of the effects of different nighttime factors. The methodology is explained using a case study of a nighttime asphalt paving operation.

In this methodology, the nighttime qualitative factors affecting the productivity of the operation were identified through three avenues: conducting a literature review, observing and analyzing nighttime operations, and interviewing subject matter experts (SMEs). In a case study of a nighttime asphalt paving project on Interstate 65 in Indiana, the effects of these factors on the productivity of the operation were determined by the personnel involved in that project. Significant factors (i.e., those exhibiting a large effect on productivity rates) were identified based on their weights, which signify the level of importance assigned to each factor by the project personnel. The PI was then calculated using a QFW model. A discrete event simulation was used to obtain an estimate of the expected baseline productivity of the case study project. This estimated baseline productivity was modified using the calculated PI value to reflect disruptions in the operation caused by nighttime factors. The results were compared with the actual productivity rates of the project.

Literature Review

A considerable body of knowledge exists in the field of construction productivity. Literature related to the productivity of labor-intensive projects, equipment-intensive projects, and nighttime operations is discussed in this section to identify the gaps in knowledge regarding assessment of the productivity of nighttime operations.

Studies Related to Labor-Intensive Projects

The majority of the current literature focuses on the productivity of labor-intensive projects: see, for example, Thomas et al. (1998, 1999, 2002, 2003); Thomas and Napolitan (1995); Horner and Talhouni (1993); Burleson et al. (1998). These studies focused on assessment of workflow management (i.e., using the principles of production theory in the manufacturing industry to evaluate the causes of productivity variability in construction projects), factors that affect improvement of productivity in labor-intensive projects, causes of loss of labor efficiency, quantification of the loss of labor efficiency, productivity drivers, and strategies. Furthermore, these studies focused on assessment of the productivity of projects with daytime operations only.

Studies Related to Equipment-Intensive Projects

Maintaining continuity in the work pattern of a crew is important for equipment-intensive projects, such as asphalt paving, because the equipment typically used in such operations is expensive (Vorster and De La Garza 1990). Relative to studies related to labor-intensive projects, research on workflow management and the factors that cause disruptions in equipment-intensive operations has not been as extensive (Choi and Minchin 2006). Schmitt et al. (1997) provided a systems approach for measuring and improving the use of asphalt paving resources with established productivity methods. A study conducted by Choi and Minchin (2006) measured the daily production rates of four highway pavement construction projects in Florida during 2004, verified the factors that adversely affected performance, and quantified the loss of work hours caused by each factor. The studies by Schmitt et al. (1997) and Choi and Minchin (2006) focused only on daytime projects.

The productivity of equipment-intensive operations can be calculated based on the productivity of the crew and the equipment allocated to each task. In deterministic and simulation approaches, the baseline productivity of the paver can be determined based on factors such as paver speed, cycle time of the asphalt delivery trucks, and number of trucks. The baseline productivity is theoretically the ideal productivity that a crew can achieve for the activity of interest without any disruptions in operation (Thomas and Zavrski 1999). Disruptions in operations that are caused by different factors should also be taken into account to provide more realistic productivity estimations. Groups of factors that cause disruptions in an operation include management, work content, and weather factors (Choi and Minchin 2006), in addition to nighttime factors.

Studies Related to Nighttime Projects

In the field of equipment-intensive project productivity, a few studies have focused on productivity in nighttime highway operations. Ellis et al. (1993), Dunston et al. (2000), and Colbert (2003) concluded that there is no variation in nighttime asphalt paving productivity relative to that in the daytime. In contrast, Douglas and Park (2003) stated that the productivity of nighttime asphalt paving operations is greater than that of daytime operations. In a study conducted in 2000 for the Kentucky Transportation Cabinet, Hancher and Taylor (2001) deployed surveys to other state departments of transportation, Kentucky highway contractors, and Kentucky Transportation Cabinet staff engineers to assess the problems encountered as a result of working at night. They considered different construction activities (e.g., asphalt paving, bridge construction, and excavation), and asserted that the factors related to working at night exert negative impacts on productivity, which may be significant or negligible, depending on the characteristics of the projects. For instance, bridge deck overlay and asphalt paving operation productivity were not significantly affected by nighttime conditions. In contrast, the productivity levels of structural bridge work and rock excavation were significantly affected.

Gaps in Knowledge

Previous studies on the productivity of nighttime construction operations fall into two major categories. One set of conclusions was derived from a group of studies comparing the productivity rate records of asphalt paving operations performed at night with the same operation performed during the day: see Ellis et al. (1993); Dunston et al. (2000); and Colbert (2003). When comparing daytime versus nighttime productivity, the differences between project crew size and experience, equipment size, jobsite conditions, lighting condition, and so on were not considered. Because of the unique nature of each project and the varying project characteristics—such as the size and quantity of equipment, crew size, and jobsite conditions—it is difficult to attribute differences in productivity rates solely to nighttime factors. If the same crew and equipment were assigned to identical projects during the day and at night, it would be feasible to compare the productivity rates of the nighttime and daytime operations. If such data is not available, differences between the productivity of nighttime highway operations and daytime highway operations may not adequately reflect the effects of nighttime qualitative factors on the operation.

The second group of studies—e.g., Hancher and Taylor (2001) and Douglas and Park (2003)—captured the effect of nighttime operation on productivity by using unstructured questionnaires to obtain input from experts. The drawback of such studies is that they collected expert judgments by asking questions such as, *How would 'performance of this project at night affect productivity?* or *What problems have you encountered during nighttime operations?* Such encoding of expert judgment may encompass *cognitive biases* that may arise because of conscious or subconscious adjustments in the subjects' responses that are systematically introduced by the manner in which the subjects intellectually process their perceptions; see Spetzler and Von Holsten (1975); Barnes (1984); Kahneman et al. (1974); and Kahneman and Tversky (1996). This implies that questions of this type may not capture the true effect of nighttime factors on productivity, because the respondents would respond negatively only if they had encountered a major productivity loss and would respond positively if they had experienced significant productivity efficiency on previous projects. Furthermore, nighttime work may not necessarily improve or exacerbate productivity significantly. Thus, the previous studies related to the assessment of the effects of nighttime factors on construction productivity could be subjected to cognitive biases.

In the domain of encoding expert judgment, French (1983) contended that unguided human judgment is susceptible to many failings. In particular, he said that holistic assessment gives more weight to less important factors than a guided approach. Holistic assessment of nighttime productivity may cause a respondent only to consider the effects of some factors (e.g., the effect of lighting and visibility) as opposed to other factors, such as physical and mental fatigue, which could lead to underestimation of some factors and overemphasis of others. To ensure that cognitive biases are reduced while evaluating the productivity of construction operations at night, this study focuses on identification of specific nighttime factors and creation of a guided quantitative methodology. Thus, while the interviewees are asked about the effects of working at night on productivity, instead of providing holistic responses (such as *productivity is not affected*), they were asked to provide ratings, based on a qualitative scale, for the effects of various nighttime factors on productivity. Such a methodology facilitates consideration of various nighttime factors that may cause disruptions in the productivity of nighttime operations.

Identification of Factors Affecting Productivity of Nighttime Asphalt Paving Operations

Managers on nighttime projects are keen to ensure that the effect of the lack of natural light is reduced during nighttime operations, and hence tend to employ minimum illumination levels recommended by guidelines (Ellis et al. 2003) for working at night. However, providing minimum illumination levels does not guarantee that the productivity during nighttime operations would remain the same as those of a comparable daytime operation. There are other qualitative factors related to lighting (e.g., incoming traffic glare and difficulty in visual communication), human-related factors (e.g., physical and mental fatigue), and task-related factors (such as asphalt temperature control and material delivery) that could affect the operation's productivity at night.

In this study, the qualitative factors that cause disruptions in nighttime operations were identified through a literature review, interviews, and direct observations during multiple visits to an asphalt paving operation located on Interstate 65 in Indiana. The interviews were conducted during May—August 2009 with project superintendents, equipment operators, and workers, each with a minimum of five years of experience in nighttime highway projects. The interviews followed a preset pattern. First, the interviewees were asked to recall recent experiences pertaining to performing the activity to ensure that their answers were anchored in these experiences. Then, they were asked to describe the conditions of working at night (e.g., *Does the incoming traffic glare disrupt your performance? If so, how much?*). The responses were collected for further analysis to identify the nighttime qualitative factors. The identified factors were screened through discussions with experts, including two superintendents, each with ten years of experience in nighttime asphalt paving operations and two researchers in the field of nighttime operations. Table 1 summarizes the characteristics of the personnel interviewed to identify the factors affecting nighttime highway construction operations.

Table 2 describes the nighttime qualitative factors that were considered in this study and their classification within three groups: lighting and visibility-, task-, and human-related. Positive qualitative factors were considered along with negative qualitative factors.

Table 1. Characteristics of the Personnel Interviewed to Identify the Factors Affecting Nighttime Highway Construction Operations

Initial identification of nighttime factors	
Project visited	Personnel interviewed
I-65 asphalt paving (Jul. 6, Jul. 9, Jul. 15, Aug. 5, Aug. 25 and Oct. 31)	All the project superintendents, equipment operators, and workers involved in the project (10 interviews)
Secondary screening of factors	
Personnel interviewed	Years of experience in nighttime construction projects
Faculty (2)	Conducted extensive research related to nighttime construction operations
General superintendents (2)	Ten years in nighttime asphalt paving operations

Table 2. Qualitative Factors Affecting Productivity of Asphalt-Paving Operations

Factors	Description
Human-related	
Visual fatigue	Visual fatigue attributable to artificial lighting and improper arrangement of lighting
Physical and mental fatigue	Physical and mental fatigue attributable to irregular sleep patterns and circadian rhythms
Lighting and visibility-related	
Visual difficulties and presence of shadows	Visual difficulties in identifying the target object attributable to improper lighting arrangement and shadows
Repair of equipment after breakdown	Difficulties making repairs in the case of equipment breakdown attributable to improper lighting
Incoming traffic and lighting equipment glare	Glare caused by incoming traffic and lighting equipment
Visual communication difficulties	Difficulties in communicating visually
Task-related	
Improved material delivery times	Faster material delivery delay attributable to less traffic at night
Breaks attributable to slower equipment operation	Breaks attributable to slower equipment operation to ensure quality or to prevent potential hazards
Difficulties in equipment operations	Difficulties attributable to positioning, alignment, and so on.
Better asphalt temperature control	Faster cooling of asphalt at night (attributable to cooler temperature at night)
Reduced efficiency	Drop from 50 min of productive time per hour of operation in the first hour to 40 min of productive time per hour of operation in the sixth hour)

Positive and negative qualitative factors increase the productivity of an operation by eliminating and causing disruptions, respectively. Two positive qualitative factors were identified: faster material delivery (attributable to less traffic at night and lower demand at the asphalt plant) and faster cooling of asphalt material (thereby reducing the time lag required for cooling of the material). The other factors were categorized as negative factors because they cause disruptions.

Research Methodology

The effects of qualitative factors on the productivity of construction operations could be evaluated through a quantitative methodology to reduce cognitive biases. Zayed and Halpin (2004) and Sameh et al. (2007) proposed the qualitative factor worth model (QFW), also called the subjective factor effect model, to assess the qualitative (subjective) factors causing disruptions in a piling operation and the productivity of trenchless projects. Zayed and Halpin (2004) contended that their model is beneficial in assessing productivity using deterministic and simulation techniques. In this paper, the QFW model is used for assessing the effects of qualitative nighttime factors on the productivity of an asphalt paving operation.

The QFW model takes advantage of the analytic hierarchy process (AHP) and fuzzy logic capabilities to capture qualitative information. AHP is a well-established technique for converting subjective opinions into quantitative values and has been used in several applications, including decision-making processes. Saaty (1980) describes the steps in performing AHP as follows: hierarchical structuring of the system function and measuring the relative impacts of each element on the hierarchy.

In the QFW model, construction experts and workers determined the effectiveness values and factor weights. The effectiveness values provide a measure of the effects that each factor independently exerts on the productivity, and the weights determine the relative significance of the effect of a factor on productivity relative to other factors. The outcome of the model is the productivity index PI, which reflects the worth of the qualitative factors and their effects on the productivity of the nighttime asphalt paving operation. The PI is calculated by adding the product of the qualitative factors values and their weights (Eq. 1).

$$\mathrm{QFW}_i = V_i W_i \tag{1}$$

V_i and W_i are the effectiveness value and weight, respectively, of the *ith* factor, the latter relative to other factors. Once the QFW is calculated, the PI is determined (Eq. 2).

$$\mathrm{PI} = 1 - \Sigma\mathrm{QFW} \tag{2}$$

The construction personnel interviewed in this study were asked to rate the effectiveness values on a subjective scale using linguistic terms. The personnel inputs were translated into *effectiveness values* using the subjective performance scale, proposed by Zayed and Halpin (2004) and shown in Table 3. The weights of the factors can be either positive or negative, depending on their effect on the productivity of the paving operation. The weights of the factors are determined using pair-wise comparisons in AHP and are calculated considering the consistency ratio of the pair-wise comparison matrices. The consistency ratio CR is calculated as follows:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{3}$$

where RI is the random index that varies depending on the number of factors in the AHP problem (Saaty 1980), and CI is the consistency index, calculated as follows:

$$\mathrm{CI} = (\lambda_{\max} - m)/(m-1) \tag{4}$$

where $\lambda_{\max}$ is the maximum Eigen value in the normalized pair-wise comparison matrices and m is the number of factors in the matrices. For the matrices to be consistent, the CR should be in an acceptable range. Saaty (2003) contended that AHP allows

Table 3. Effectiveness Rating Scale of Linguistic Terms

Effectiveness	Extremely ineffective	Substantially ineffective	Moderately ineffective	Slightly ineffective	Neither ineffective nor effective	Slightly effective	Moderately effective	Substantially effective	Extremely effective
Value	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9

for inconsistency because "people are more likely to be cardinally inconsistent than cardinally consistent in making judgments due to their inability to estimate precise measurement values from a known scale and, even more so, when they deal with intangibles." However, Saaty (2003) does not set a boundary for the nearly consistent range (matrices with CR values greater than but close to 0.1 are considered to be nearly consistent).

Application of the Methodology: Nighttime Asphalt Paving Operation

The effects of nighttime factors on the productivity of asphalt paving operations are twofold: reduced equipment speeds and disruptions in the operation. The proposed methodology takes both effects into account. The methodology (Fig. 1) consists of a discrete event simulation model of the operation to facilitate simulating the baseline productivity of the operation while incorporating the effect of reduced equipment speeds attributable to working at night, and the QFW model (to calculate the PI value) to facilitate taking into account disruptions attributable to other nighttime factors.

The proposed methodology is explained in this section through its application to the assessment of the effects of nighttime factors on the productivity of an asphalt paving project on I-65 in Indiana. The asphalt paving operation process is shown in Fig. 2. The I-65 asphalt paving project (SR-30903-A), awarded in March 2009 and completed in November 2009, consisted of paving both lanes and the shoulder in both directions on I-65; specifically, on a 16 km (10 mi) stretch between mile markers 142 and 152. The contract amount was $4,275,409. Because of current interstate lane closure policies, the work could be conducted only at night, between the hours of 9:00 p.m. and 6:00 a.m. Fig. 3 shows the work zone configuration of the project and the average measured illumination at designated spots. The recommended illumination level–i.e., 108 lx for milling, paving, and compacting operations (NCHRP 2003)–were met for most of the tasks in the operation. Equipment-mounted balloon lighting equipment was used because of the mobile nature of the operation. Six site visits were conducted between May 2009 and August 2009 to collect data by direct observation, conduct interviews with field personnel, and administer questionnaires regarding the nighttime factors affecting productivity. The data collected include the illumination levels for construction tasks and the speeds of the equipment used in the operation.

Creation of the QFW Model for the Case Study

A QFW model was created for the case study project. As shown in Fig. 4, there are two levels in the QFW model for the nighttime asphalt paving operation. The first and second levels include the qualitative factor groups and the qualitative factors related to each

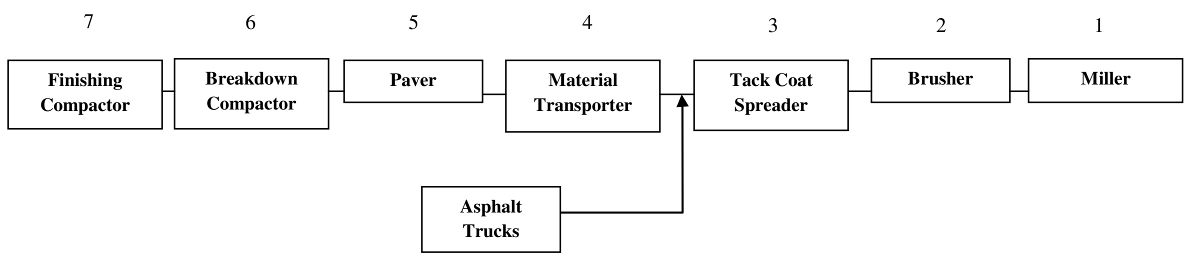
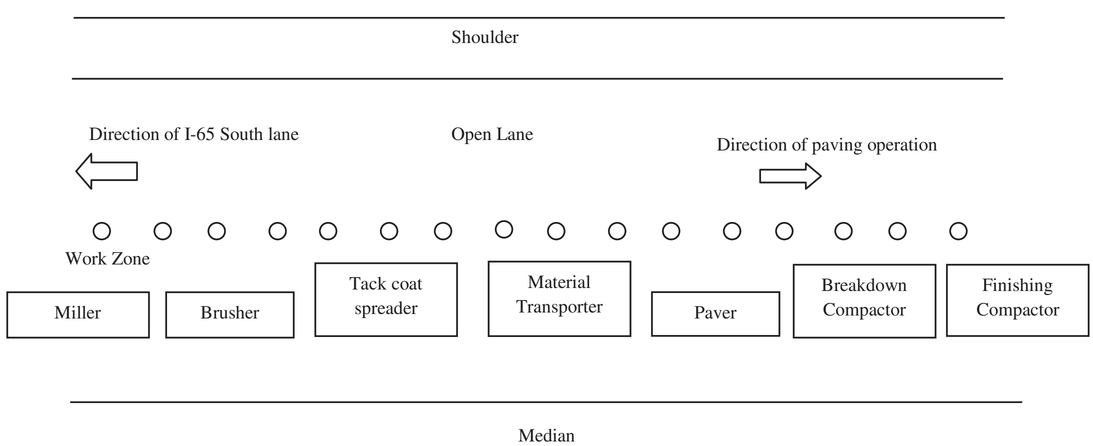


Fig. 2. Asphalt paving operation sequence



Spot	Spreader (ft from front)	Paver (ft from front)	Paver (ft from back)	Breakdown Compactor (ft from front)	Finishing Compactor (ft from front)
Illumination (lux)	65@12ft (3.68m)	124@8ft (2.44m)	218@13ft (3.96m)	216@18ft (5.5m)	165@8ft (2.44m)
Required Illumination (lux)*	108@16ft (4.88m)*	108@16ft (4.88m)	108@16ft (4.88m)	108@58ft (17.68m)	108@58ft (17.68m)

Fig. 3. I-65 project work zone configuration [*Distance to be illuminated in front and back of equipment (NCHRP 2003)]

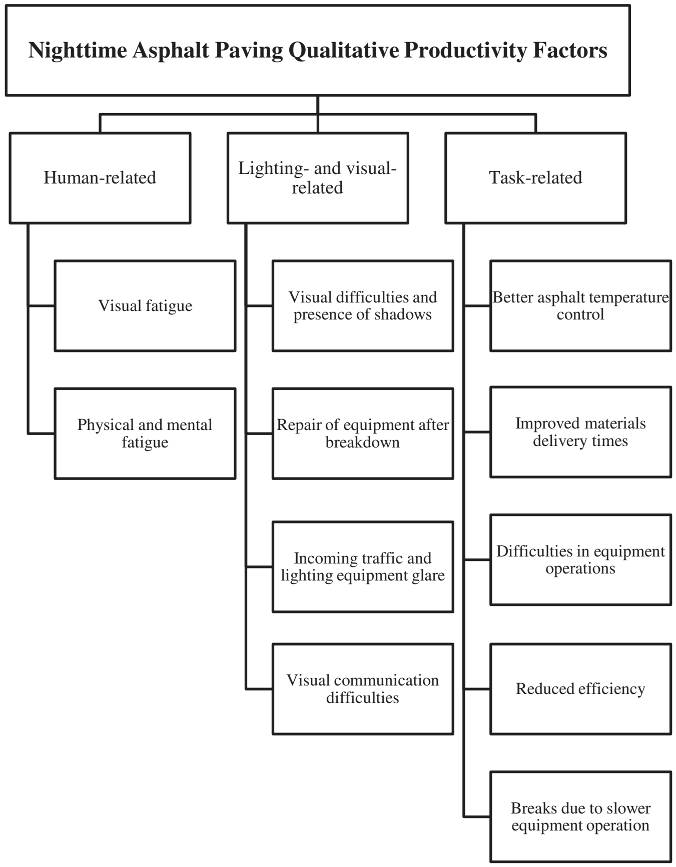


Fig. 4. Nighttime qualitative factors hierarchical structure

group, respectively. This hierarchical structure was used to evaluate the relative importance (weight) of the factors, which were categorized based on their type of effect on productivity. For instance, those factors that affect productivity by reducing visibility were categorized as lighting- and visibility-related factors. Similarly, those factors that affect productivity by improving or reducing operational task efficiencies were categorized as task-related factors. The nighttime qualitative factors might belong to more than one classification; for instance, visual fatigue could be classified under both lighting and visibility-related in addition to human-related groups of factors. However, to limit the level of detail in the analysis, the factors were classified under the most representative group.

The effectiveness values and weights of the qualitative factors that are used in the QFW model to calculate the operation's PI were determined using a questionnaire survey administered to the members of the I-65 project crew, including the supervisor, the engineer, equipment operators, and laborers (a total of eight respondents). The respondents were asked to determine the effectiveness values and weights of the qualitative factors (e.g., *On a scale of 1–9, how do you rate the effect on productivity of each one of the following factors?* or *Using pair-wise comparisons, how do you express the relative importance of one factor over the other?*). As shown in Table 4, material delivery, repair of equipment after breakdown, physical and mental fatigue, and visual communication difficulties were rated as exerting the greatest effects on productivity, with respective effectiveness values of 0.55, 0.475, 0.45, and 0.425, and respective standard deviations of 0.18, 0.2, 0.18, and 0.15. At each level in the hierarchy, the effectiveness values were weighted using AHP pair-wise comparison matrices. The pair-wise comparison matrix has a value of 1 in the main diagonal, and the elements below the main diagonal are reciprocal to the elements above it ($a_{ij} = 1/a_{j,i}$, where a_{ij} represents the weight of factor i relative to factor j.

The pair-wise comparison matrices were normalized to calculate the relative weights of the factors. Consequently, the consistency ratios CR were calculated for each matrix. In calculation of CR values, using Eqs. 3 and 4, m is the size of the pair-wise comparison matrix and RI is the random index that varies depending on the number of elements in the matrix. For example, in the pair-wise comparison matrix of factor groups, there were three elements (i.e., lighting and visibility-related, human-related, and task-related); thus, m was equal to 3, CI was equal to 0.0193, and RI was equal to 0.58 for a pair-wise comparison matrix with three elements, according to the RI values presented by Saaty (1980), yielding a CR value of 0.0332. In the analysis of all matrices, one pair-wise comparison matrix [corresponding to respondent identification (ID) number 4] was found to be inconsistent, and was hence eliminated

Table 4. Effectiveness Values of Nighttime Factors

Respondent ID	1	2	3	4	5	6	7	8	
Job position	Paver operator	Laborer	Roller operator	Laborer	Superintendent	Superintendent	Paver operator	Superintendent	Average (SD)
Years of experience	5	3	10	13	17	20	20	10	
Subjective factors									
Visual difficulties and presence of shadows	0.3	0.3	0.3	0.3	0.5	0.5	0.3	0.3	0.35 (0.09)
Incoming traffic and lighting equipment glare	0.3	0.3	0.3	0.3	0.5	0.5	0.3	0.3	0.35 (0.09)
Visual fatigue	0.3	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.325 (0.07)
Physical and mental fatigue	0.7	0.3	0.5	0.3	0.5	0.7	0.3	0.3	0.45 (0.18)
Breaks attributable to slower equipment operation	0.1	0.5	0.5	0.3	0.5	0.1	0.3	0.3	0.325 (0.17)
Visual communication difficulties	0.7	0.5	0.3	0.3	0.5	0.5	0.3	0.3	0.425 (0.15)
Difficulties in equipment operations	0.7	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.375 (0.15)
Repair of equipment after breakdown	0.5	0.7	0.3	0.3	0.7	0.7	0.3	0.3	0.475 (0.2)
Reduced efficiency	0.1	0.5	0.3	0.3	0.5	0.3	0.3	0.3	0.325 (0.13)
Improved material delivery times	0.3	0.3	0.7	0.7	0.5	0.5	0.7	0.7	0.55 (0.18)
Better asphalt temperature control	0.3	0.5	0.3	0.3	0.3	0.5	0.3	0.3	0.35 (0.09)

Table 5. Average Weights of Factors in Each Group and Group Weights

Group 1: Lighting- and visibility-related factors	Importance weights	Ranking
Visual difficulties and presence of shadows	0.56	1
Incoming traffic and lighting equipment glare	0.06	4
Repair of equipment after breakdown	0.12	3
Visual communication difficulties	0.26	2
Group 2: Task-related factors	**Importance weights**	**Ranking**
Breaks attributable to slower equipment operation	0.48	1
Difficulties in equipment operations	0.27	2
Better asphalt temperature control	0.03	5
Improved material delivery times	0.16	3
Reduced efficiency	0.06	4
Group 3: Human-related factors	**Importance weights**	**Ranking**
Visual fatigue	0.22	2
Physical and mental fatigue	0.78	1
Groups	**Importance weights**	**Ranking**
Lighting- and visibility-related	0.21	3
Task-related	0.25	2
Human-related	0.54	1

from the analysis. The remaining pair-wise comparison matrices were either consistent ($CR < 0.1$) or nearly consistent ($CR < 0.3$), which are acceptable according to Saaty (2003).

Table 5 lists the average weights and rankings of the factors in each group and also displays the average weights of the groups of factors. For the case study, the human-related factors were rated as the most important groups of factors affecting productivity, with an importance weight of 0.54. Lighting- and task-related factors were almost equally weighted: 0.21 and 0.25, respectively, based on their effects on productivity. At the lower level of the hierarchy, visual difficulty in identifying the target objects was rated as the most important lighting factor affecting productivity, with an importance weight of 0.56, even though the work zone lighting met the minimum illumination level for most of the tasks. Visual communication was rated as the second important lighting-related factor, with an importance weight of 0.26. In addition, breaks attributable to slower equipment speed, to ensure quality and safety, was ranked first among the task-related factors affecting productivity, with an importance weight of 0.48. Equipment positioning and alignment was the second most important task-related factor affecting productivity, with a weight of 0.27. Physical and mental fatigue was determined to be more important (weight of 0.78) than visual fatigue (weight of 0.22) when considering human-related factors.

The final weight of a factor was calculated by multiplying the weight of the factor in the lower hierarchy by that of the respective factor group. For instance, the ultimate weight of the visual communication factor (0.05) was calculated by multiplying the factor weight (0.26) by the weight of the lighting group (0.21). The final weights of the factors are shown in Table 6. Physical and mental fatigue was the dominant factor affecting productivity, with an average weight of 0.45 and a standard deviation of 0.11. Breaks attributable to slower equipment operation, visual fatigue, and visual difficulties were the subsequent most important factors, with respective average weights of 0.13, 0.11, and 0.09, and respective standard deviations of 0.07, 0.09, and 0.03. Positive factors, such as material delivery and asphalt temperature control, had weights of 0.04 and 0.01 and standard deviations of 0.01 and 0.00, respectively.

Table 6. Final Weights of Factors

Lighting factors	Importance weights (SD)	Ranking
Visual difficulties and presence of shadows	0.09 (0.03)	4
Incoming traffic and lighting equipment glare	0.01 (0.01)	11
Repair of equipment after breakdown	0.02 (0.01)	9
Visual communication difficulties	0.05 (0.00)	6
Task factors	**Importance weights (SD)**	**Ranking**
Breaks attributable to slower equipment operation	0.13 (0.07)	2
Difficulties in equipment operations	0.07 (0.06)	5
Better asphalt temperature control	0.01 (0.00)	10
Improved material delivery time	0.04 (0.01)	7
Reduced efficiency	0.02 (0.00)	8
Human factors	**Importance weights (SD)**	**Ranking**
Visual fatigue	0.11 (0.09)	3
Physical and mental fatigue	0.45 (0.11)	1

Determination of these relative weights facilitated calculation of the QFW and subsequently the PI. The QFW was calculated by summing the multiplication of the final relative weights of the factors (Table 6) by their average effectiveness values (Table 4). The effects of the positive factors (i.e., better material delivery times and better asphalt temperature control) were subtracted from the QFW because they improve productivity. The PI was calculated as follows:

$$\mathrm{PI} = 1 - \Sigma\mathrm{QFW} = 1 - 0.35 = 0.65$$

The calculated PI was then used to modify the baseline productivity estimated using the simulation model described in the following section.

Simulation Model of the Case Study Operation

The baseline productivity is a measure of the production level that the project crew and equipment can achieve when there are no disruptions in the operation. In this study, the model for determining the baseline productivity was built using the STROBOSCOPE (Martinez 1996) discrete event simulation package in addition to the data related to the speed of equipment and the tasks' lead times from the case study project. Discrete event simulation was adopted in this study to estimate the baseline productivity because reliable historical data were not available for the case study and there is a solid body of knowledge indicating that discrete event simulation provides a good estimation of the productivity of construction operations. Discrete event simulation is a method of modeling an operation as a chronological sequence of events. STROBOSCOPE is a construction-oriented discrete event simulation package that has a very intuitive and user-friendly graphical user interface. Discrete event simulation is used to estimate the baseline productivity to incorporate project-specific characteristics, such as equipment size and experience of the project crew. Discrete event simulation provides a more realistic assessment of the dynamics of construction operations. It provides a basis to model the interdependencies of different equipment and the uncertainties related to the duration of different tasks (Martinez 2010). These interdependencies and uncertainties cannot be fully captured using a deterministic approach in which the productivity of the operation is controlled

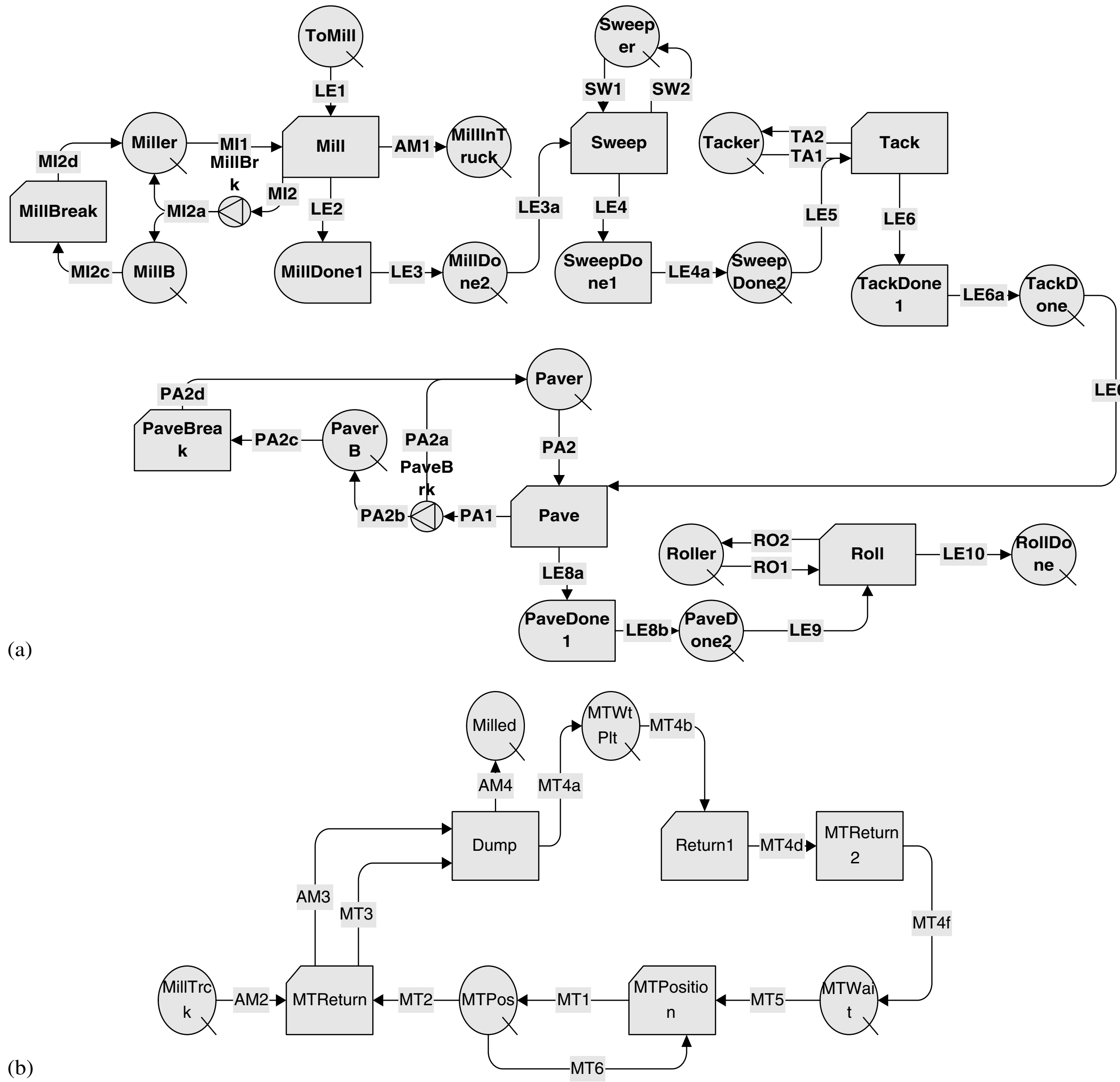


Fig. 5. (a) Mainline paving operation; (b) cycle of the milling truck

by the productivity of the bottleneck equipment. In construction operations, there could be situations in which the productivity of the operation is controlled not only by the bottleneck equipment, but also by the interdependencies between the tasks and the uncertainties in task durations. Discrete event simulation provides a tool for incorporating these dynamics into the analysis. According to Song and AbouRizk (2008) and Motwani et al. (1995), historical project data lack a consistent productivity measurement system and the low quality of historical data may prevent a meaningful analysis of productivity. Thus, the project-specific characteristics may not be taken into account if baseline productivity rates are obtained from the historical records. A detailed description of the model used in this study can be found in Louis (2010).

For modeling purposes, the asphalt paving operation was broken down into three different cycles: the mainline paving, milling truck, and asphalt truck cycles. The mainline paving cycle was modeled by considering the flow of the resource length through the various activities of the operation. Length refers to the length of pavement required to be resurfaced and is contained in the queue ToMill. During each cycle, 30.5 m (100 ft) of pavement is worked by each activity. It was necessary to discretize what is essentially a continuous process because the duration data was collected for the time taken to perform an activity on 100 ft of pavement. Initially the surface of 100 ft of pavement is removed during the Mill activity using the Miller resource. This process produces milled asphalt that is loaded onto a waiting milling truck. Once the pavement is milled, the Sweep activity is performed to clear the debris off the pavement using the Sweeper resource. Then, the Tacker resource applies a tacking coat on the pavement that is required to ensure a strong bond between the new coat of asphalt and the existing pavement. After the tack coat has been applied, a Paver resource is used to apply a layer of fresh hot mix asphalt (HMA) delivered by asphalt trucks. Once the HMA has been laid, a Roller resource is used to compact the HMA. In the discrete event simulation model, the effect of late delivery of asphalt material would lead the productivity to drop to zero. The section of the discrete event simulation model representing this process is shown in Fig. 5(a).

Table 7. Probability Distributions Used in the Discrete Event Simulation

Variable description	Distribution
Lead given by the sweeper to the miller	Uniform [30.5,45.7] m (Uniform [100,150] ft)
Lead given by the tacker to the sweeper	Uniform [30.5,45.7] m (Uniform [100,150] ft)
Lead given by the paver to the tacker	Uniform [30.5,45.7] m (Uniform [100,150] ft)
Lead given by the roller to the paver	Uniform [30.5,45.7] m (Uniform [100,150] ft)
Speed of the miller	0.51 m/s (100 ft/min)
Speed of the sweeper	Uniform [0.3,0.35] m/s (Uniform [60,70] ft/min)
Speed of the tacker	0.3 m/s (60 ft/min)
Speed of the finishing roller	0.25 m/s (50 ft/min)

The model for the milling truck cycle is shown in Fig. 5(b). Once there is sufficient milled asphalt in the truck, it returns to the asphalt plant where the milled asphalt is dumped. The empty truck then returns to the work site and waits to be filled by the milling machine. The asphalt truck cycle is very similar to the milling truck cycle, with the difference being that it hauls freshly prepared HMA to the site from the plant and unloads it into the material transfer vehicle.

The inputs for the simulation model include the number and size of the different resources utilized (e.g., the number and size of trucks), thickness of the HMA layer, lane width, speed of the equipment (e.g., speed of the miller and roller), and the tasks' lead times (e.g., lead given by the paver to the tacker, and lead given by the roller to the paver). The equipment fleet consisted of five trucks with the capacity of 600 ft^3 (17 m^3) for hauling milled material, five trucks with the capacity of 600 ft^3 (17 m^3) for hauling asphalt from the plant, one miller, one sweeper, one tack coat spreader, one material transfer vehicle, one pavement machine, and two rolling compactors. The thickness of the asphalt was 1.5 in (38 mm) and the lane width was 12 ft (3.7 m). The task durations were collected on the basis of the time taken to implement each task in 100 ft (30.5 m) length intervals. The probability distributions related to the speed of the equipment and the lead times of the tasks are presented in Table 7. The distributions of all the equipment speeds and lead times were obtained during site visits in the July–October 2009 time frame. The best distributions for the collected data were obtained based on the distribution fitting techniques. A detailed description of the data, fitted probability distributions, and model used in this study can be found in Louis (2010).

Data related to the speed of the equipment and task lead times were collected during site visits to the project. The data was analyzed and used to estimate the probability distribution of the task durations. Because the fitted probability distributions corresponding to the task durations were estimated using the actual nighttime data from the case study project, the effects of nighttime factors on the operating speed of the equipment (e.g., speed reduction as a result of incoming traffic glare) and the lead times were reflected in the distributions used in the discrete event simulation model. However, the discrete event simulation model estimates the baseline productivity assuming no disruptions in the operation attributable to other nighttime factors. In addition to a reduction in equipment speed and increased lead times, other nighttime factors, such as breaks attributable to operator fatigue and difficulties in visual communication, may cause disruptions in the operation. The objective for incorporating the PI value was to quantify the disruptions in the operation caused by nighttime factors, such as breaks attributable to incoming traffic glare, difficulties in visual communication, operator fatigue, and so on for a particular job, which cannot be captured using the simulation model alone.

Several runs of the STROBOSCOPE simulation were performed to obtain the simulated baseline productivity. The simulation results estimated the productivity with a uniform distribution and mean productivity of 0.31 mi/h (0.14 m/s). Then, the simulation productivity distribution was multiplied by the PI. The PI-modified simulation results indicate that the mean productivity of the operation was 0.2 mi/h (0.089 m/s), and 90% of the simulated productivity rates were between 0.19 and 0.21 mi/h (0.084 and 0.094 m/s).

Accounting for Other Disruptions in the Operation

There are other expected disruptions in the asphalt paving operation that reduce productivity. In addition to nighttime factors, weather, work content, and management factors (Choi and Minchin 2006) can also cause disruptions in operations. The weather factor effects were not considered in this case study because the operation did not take place during unfavorable weather conditions such as rain and storms. Disruptions attributable to work content, such as the paver stopping to adjust its distance to the miller, were incorporated in the operation simulation model by using correlated (nonindependent and identically distributed) task duration distributions collected during site visits to the project (Louis 2010). Management disruptions are typically categorized as problems with prerequisite work, out-of-sequence work, rework, work conflict, work area, and material shortage (Choi and Minchin 2006). These disruptions were not observed during the six site visits to the project under consideration.

Comparison of the Modified Simulated Productivity with Actual Productivity

The results of the simulation were compared with the actual productivity rates of the paving operation case study. The actual productivity rates were collected from the Indiana Department of Transportation (INDOT) and were recorded as the number of miles paved per working shift. The hourly productivity was determined by assigning a project evaluation and review technique (PERT) distribution (modified Beta distribution) to the duration of the shifts with a minimum, most probable, and maximum of 5, 6, and 7 h/shift, respectively. These values were assigned based on the information records (the project was required to be executed during the 9:00 p.m.–6:00 a.m. time frame). It generally took 45 min to 1 h for setup and tear down, which resulted in approximately 7 h dedicated per night to the actual paving operation. The actual hourly productivity was calculated by dividing the distribution of the shift productivity by the distribution of hours per shift. Fig. 6 shows the actual productivity distribution in mi/h. These results indicate that the productivity mean of the operation was 0.23 mi/h (0.10 m/s), and 90% of the actual productivity rates were between 0.22 and 0.23 mi/h (0.098 and 0.10 m/s).

To determine the closeness of the simulation productivity model results to the actual productivity rates, the validation factor (VF) proposed by Zayed and Halpin (2004) was used. The VF distribution was simulated by dividing the modified simulated productivity distribution by the actual productivity distribution. The VF distribution (shown in Fig. 7) exhibits a mean of 0.89, and 90% of the VF values were between 0.83 and 0.93. These results indicate that the modified estimated productivity of the case study can represent the actual productivity with an acceptable accuracy. This is an acceptable range of productivity estimation, implying that the calculated nighttime PI has captured the effects of the nighttime factors on productivity to an acceptable extent for the project under consideration.

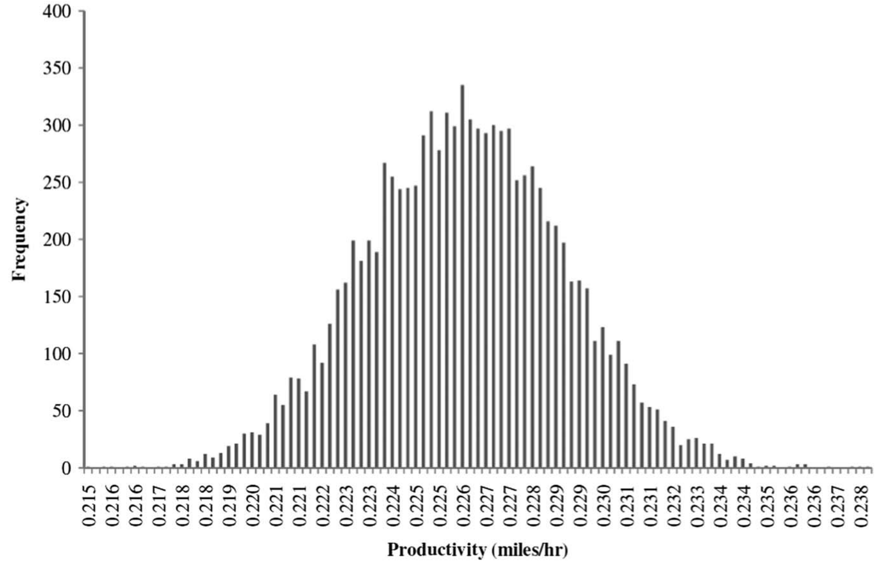


Fig. 6. Actual productivity distribution based on the collected data

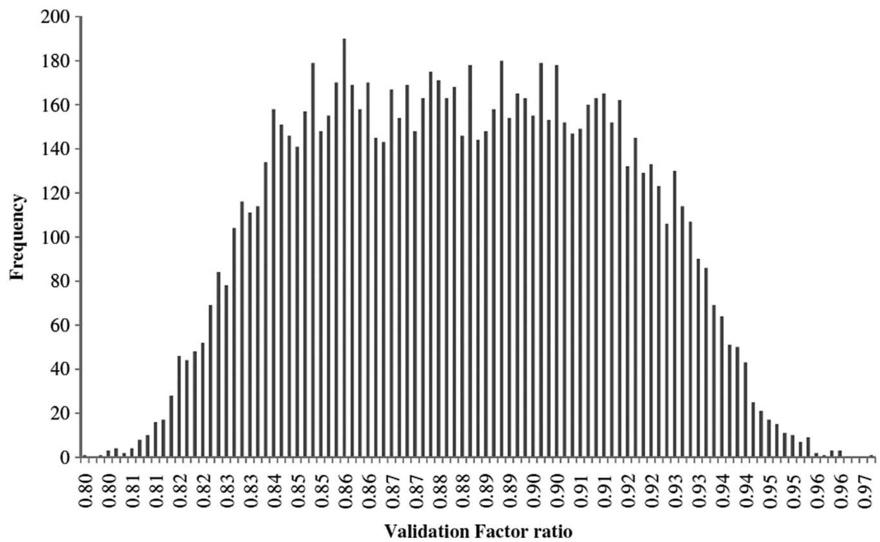


Fig. 7. Validation factor distribution

To better illustrate the advantage of the proposed methodology using discrete event simulation, the results were compared with those of deterministic approaches. Although the probability distributions related to some of the equipments' speed are deterministic, the interdependencies of different equipment cannot be completely captured using deterministic approaches. If a deterministic approach was used in this case study for estimating the baseline productivity, the productivity of the operation would be governed by that of the bottleneck equipment (i.e., the paver). The average speed of the paver was 45 ft/ min. Thus, the baseline productivity of the paver would be calculated as follows:

$$\begin{aligned} \text{operation productivity} &= \text{paver productivity} \\ &= [45\,(\text{ft/min}) \\ &\quad \times 60\,(\text{min/h})]/5280\,(\text{ft/mi}) \\ &= 0.511\,(\text{mi/h}) \end{aligned} \tag{5}$$

If this deterministic baseline productivity was modified using an operating factor (50 min/hr) to reflect the disruptions in the operation attributable to management-related factors and work content-related factors (Schaufelberger 1999), in addition to the productivity index (0.65) to reflect the disruptions in the operation attributable to nighttime factors, the modified estimated productivity could be obtained. Note that the operating factor for the deterministic approach was assumed to be 50 min/h, because the occurrences of management-related disruptions (e.g., prerequisite work, out-of sequence work, rework, and work conflict) were not observed during the six site visits to the project under consideration. The modified estimated productivity using the deterministic approach would be equal to 0.28 mi/h. However, 90% of the actual productivity rates were between 0.22 and 0.23 mi/h. Thus, the validation factor obtained from the deterministic approach would be equal to 1.27 (i.e., 27% overestimation), whereas the mean of the validation factor obtained from the discrete event simulation was 0.89 (i.e., 11% underestimation). Thus, the estimated productivity using the discrete event simulation led to a better estimation of the productivity relative to the deterministic approach.

Summary and Conclusion

Qualitative factors—e.g., lighting and visibility-, human-, and task-related factors—affect the productivity of nighttime operations by causing disruptions in the operation. The existing body of knowledge has not quantified the impact of these factors. Furthermore, because of project-specific characteristics (e.g., experience of the crew, size of the equipment, speed of the equipment, and management condition of the jobsite), historical data (from previous projects) to estimate productivity is not reliable. This paper identified the qualitative factors linked to nighttime construction operations and provided a structured methodology for assessing the effect of these factors on the productivity of asphalt paving operations. The methodology used discrete event simulation to account for project-specific characteristics and the qualitative factor worth model to quantify the effects of nighttime factors.

The qualitative factors affecting the productivity of asphalt paving operations were identified and categorized into three groups: lighting- and visibility-, task-, and human-related. A nighttime productivity index accounted for the effects of the identified factors on productivity to modify the baseline productivity estimate obtained from the simulation model of a typical asphalt paving operation. The productivity index (PI) was determined using a subjective factor effect model using input from the personnel involved with nighttime paving operations. The PI of the case study operation was calculated to be 0.65, and was used to adjust the simulation model's estimated productivity rates to account for the disruptions attributable to nighttime factors. The modified simulated productivity rates were validated using the actual productivity rates from the project. The validation factor values revealed that the model could predict the productivity of the case study within an acceptable range. The result implies that the calculated nighttime PI has captured the effects of the nighttime factors on productivity to an acceptable extent for the project under consideration.

The primary contribution of this study to the body of knowledge is quantification of the effects of qualitative nighttime factors on the productivity of asphalt paving operations. No prior studies have adopted a methodology to quantify these effects. The quantification of the effects of nighttime factors could help practitioners understand the extent of their effects on projects. Because nighttime operations are usually more expensive—attributable to overtime payments, night premium payments, lighting expenses, and costs associated with enhanced traffic control—a better estimate of nighttime productivity is crucial. Because historical data of previous projects may not be very reliable for productivity estimation, the methodology proposed in this paper could facilitate incorporation of project-specific characteristics and qualitative nighttime factors. The advantage of this methodology is that it is useful for understanding and quantifying the effects of nighttime factors on productivity. The extent of such effects is attributable to different factors, such as the experience of the workers, lighting conditions, and work zone conditions. This case study shows that the proposed methodology provides a tool for quantifying the extent of the effects of nighttime factors on a project using the data obtained from the specific project. Such information can be used not only during the planning stage, but also during the early period of the execution phase of the project to reduce the negative effects of nighttime factors. For instance, the proposed methodology could be used to identify the most significant factors affecting the productivity of the operation such that the project engineers could adopt appropriate strategies to reduce the resulting negative effects.

The proposed methodology is capable of being applied and tested for productivity estimation and planning of other nighttime construction operations. The calculated PI would not be the same for every project, and instead depends on the experience of the project crew in nighttime projects and other work zone condition factors, such as the lighting condition, size of the equipment, and crew size. However, a similar approach can be adopted to calculate the PI for other asphalt paving projects to modify baseline productivity, and consequently derive more realistic productivity estimations. Practitioners could adopt the approach developed in this study for understanding the extent of the effects of nighttime factors on the productivity of their projects. Baseline productivity of the operation could be simulated using discrete event simulation. The data required to build the discrete event simulation model include the speed of the equipment, lead times of the tasks, and interdependencies of different tasks. These data could be obtained from the historical records of similar projects, collected from the project in early stages of execution, or assumed based on estimates provided by project engineers. In the last case, project engineers could use PERT distributions, for example, and estimate the best, most likely, and worst case values related to the speeds of the equipment and lead times of the tasks. After estimating the baseline productivity, the project crew could be asked to determine the weights and effectiveness values of the nighttime factors, as illustrated in this case study, to calculate the productivity index using the quantitative factor worth model. The baseline productivity could then be modified using the productivity index.

Additional studies are needed to expand the methodology presented in this paper to quantification of the effects of qualitative nighttime factors on the productivity of other nighttime construction projects. Another approach to do so would be to integrate the effects of nighttime factors (e.g., lighting, operator fatigue, equipment breakdown) up front in the simulation. This approach is possible if appropriate variables and probability distributions, based on actual field data collection, are added to the simulation model. Future research could also create an approach to consider the effects of nighttime factors on different tasks (e.g., milling, paving, and compaction) separately, and then the resulting impacts on the entire operation could be measured. Studies could be conducted to analyze projects with different levels of illumination levels and uniformity to perform a statistical analysis to quantify the effects of these factors specifically on the productivity of asphalt paving projects. Furthermore, the proposed model could be used to assess the effects of nighttime factors in different projects. Then, using statistical analysis, the level of accuracy of the proposed methodology in quantifying the effects of nighttime factors and estimating the productivity could be compared across different projects. Because of the large number of nighttime asphalt paving projects in the U.S., implementing a rigorous statistical analysis requires collecting data from a sample that consists of several projects. For such an analysis, projects with different characteristics (such as equipment size, work zone conditions, lighting conditions, the level of experience of the workers and operators in nighttime operations) should be considered and data related to these characteristics should be collected. The methodology shown in Fig. 1 could be adopted to incorporate project-specific characteristics in estimating the baseline productivity and productivity index for each project. Data related to the speeds of the equipment and the lead times of the tasks should be collected to build the discrete event simulation model for each project. Then, the proposed qualitative factor worth model could be implemented for each project by collecting data related to the weights and effectiveness of the nighttime factors from the project crew. Using the qualitative factor worth model, the productivity index for each project can be obtained. Then, for each project, the modified estimated productivity values could be compared with the productivity values as obtained from project records to obtain the accuracy of the proposed methodology. Statistical analysis could then be used to obtain the mean and standard deviation of the productivity index values and the level of accuracy of the estimated productivity rates, and also to compare the effects of project-specific characteristics on the estimated baseline productivity and productivity index values. The proposed approaches and their outcomes can be compared with the methodology presented in this paper to extend the body of knowledge by obtaining a better understanding of the effects of nighttime factors on the productivity of construction operations, and extend the body of practice by creating improved methodologies for quantification of the effects of nighttime factors on the productivity of construction projects as an aid in project planning and managing.

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References

Al-Kaisy, A., and Nassar, K. (2009). "Developing a decision support tool for nighttime construction in highway projects." *J. Constr. Eng. Manage.*, 135(2), 119–125.

Barnes, J. H. (1984). "Cognitive biases and their impact on strategic planning." *Strateg. Manage. J.*, 5(2), 129–137.

Burleson, R. C., Haas, C. T., Tucker, R. L., and Stanley, A. (1998). "Multi-skilled labor utilization strategies in construction." *J. Constr. Eng. Manage.*, 124(6), 480–489.

Choi, J., and Minchin, R. E. (2006). "Workflow management and productivity control for asphalt pavement operations." *Can. J. Civ. Eng.*, 33(8), 1039–1049.

Colbert, D. A. (2003). "Productivity and safety implications of night-time construction operations." *Independent Research Study Rep.*, Purdue Univ., West Lafayette, IN.

Douglas, K. D., and Park, S. B. (2003). "Selection criteria for using nighttime construction and maintenance operations." *Rep. SPR 322*, Oregon State Univ., Corvallis, OR.

Dunston, P. S., Savage, B. M., and Mannering, F. L. (2000). "Weekend closure for construction of asphalt overlay on urban highway." *J. Constr. Eng. Manage.*, 126(4), 313–319.

Ellis, R. D., Herbsman, Z. J., Chheda, P. N., Epstein, W. C., and Kumar, A. (1993). "Developing procedures for night operations of transportation construction projects." *Rep. No. UTC-UF-326-93-1*, Transportation Research Center, Univ. of Florida, Gainesville, FL.

Ellis, R. D., Jr., Amos, S., and Kumar, A. (2003). "Illumination guidelines for nighttime highway work." *Rep. No. 498*, National Cooperative Highway Research Program, Washington, DC.

Federal Highway Administration (FHWA). (2008). "Facts and statistics—FHWA work zone." ⟨http://ops.fhwa.dot.gov/wz/resources/facts_stats.htm⟩ (Mar. 5, 2010).

French, S. (1983). "A survey and interpretation of multi-attribute utility theory." *Multiobjective decision making*, Academic Press, London.

Hancher, D., and Taylor, T. (2001). "Nighttime construction issues." *J. Transport. Res. Board*, 1761(1), 107–115.

Horner, R. M. W., and Talhouni, B. T. (1993). "Effects of accelerated working, delays and disruptions on labor productivity." *Special Rep.*, The Chartered Institute of Building, London.

Kahneman, D., Slovic, P., and Tversky, A. (1974). "Judgment under uncertainty: Heuristics and biases." *Science*, 185(4157), 1124–1131.

Kahneman, D., and Tversky, A. (1996). "On the reality of cognitive illusions." *Psychol. Rev.*, 103(3), 582–592.

Louis, J. (2010). "Impact of lighting on the safety and productivity of nighttime construction workers." MSCE thesis, School of Civil Engineering, Purdue Univ., West Lafayette, IN.

Martinez, J. C. (1996). "STROBOSCOPE: State and resource-based simulation of construction processes." Doctoral dissertation, Dept. of Civil and Environmental Engineering, Univ. of Michigan, Ann Arbor, MI.

Martinez, J. C. (2010). "Methodology for conducting discrete-event simulation studies in construction engineering and management." *J. Constr. Eng. Manage.*, 136(1), 3–16.

Motwani, J., Kumar, A., and Novakoski, M. (1995). "Measuring construction productivity: A practical approach." *Work Study*, 44(8), 18–20.

National Cooperative Highway Research Program (NCHRP). (2003). "Illumination guidelines for nighttime highway work." *Rep. 498*, Transportation Research Board, Washington, DC.

Saaty, T. (1980). *The analytic hierarchy process*, McGraw-Hill, New York.

Saaty, T. (2003). "Decision-making with the AHP: Why is the principal eigenvector necessary?" *Eur. J. Oper. Res.*, 145(1), 85–91.

Sameh, A., Zayed, T., and Hegab, M. (2007). "Modeling the effect of subjective factors on productivity of trenchless technology application to buried infrastructure systems." *J. Constr. Eng. Manage.*, 133(10), 743–748.

Schaufelberger, J. E. (1999). *Construction equipment management*, Prentice-Hall, Upper Saddle River, NJ.

Schmitt, R. L., Hanna, A. S., and Russell, J. S. (1997). "Improving asphalt paving productivity." *J. Trans. Res. Board*, 1575, 23–33.

Song, L., and AbouRizk, S. (2008). "Measuring and modeling labor productivity using historical data." *J. Constr. Eng. Manage.*, 134(10), 786–794.

Spetzler, C. S., and Staël von Holstein, C. S. (1975). "Probability encoding in decision analysis." *Manage. Sci.*, 22(3), 340–358.

Thomas, H. R., Horman, M. J., de Souza, U., and Završki, I. (2002). "Reducing variability to improve performance as a lean construction principle." *J. Constr. Eng. Manage.*, 128(2), 144–154.

Thomas, H. R., Horner, R. M. W., Završki, I., and de Souza, U. (1998). "Principles of construction labor productivity measurement and processing." *Final Rep.*, Pennsylvania Transportation Institute, Pennsylvania State Univ., University Park, PA.

Thomas, H. R., Minchin, R. E. Jr., Horman, M. J., and Chen, D. (2003). "Improving labor flow reliability for better productivity as a lean construction principle." *J. Constr. Eng. Manage.*, 129(3), 251–261.

Thomas, H. R., and Napolitan, C. L. (1995). "Quantitative effects of construction changes on labor productivity." *J. Constr. Eng. Manage.*, 121(3), 290–296.

Thomas, H. R., Riley, D. R., and Sanvido, V. E. (1999). "Loss of labor productivity due to delivery methods and weather." *J. Constr. Eng. Manage.*, 125(1), 39–46.

Thomas, H. R., and Zavrski, I. (1999). "Construction baseline productivity: Theory and practice." *J. Constr. Eng. Manage.*, 125(5), 295–303.

Vorster, M. C., and de la Garza, J. M. (1990). "Consequential equipment costs associated with lack of availability and downtime." *J. Constr. Eng. Manage.*, 116(4), 656–669.

Zayed, T. M., and Halpin, D. W. (2004). "Quantitative assessment for piles productivity factors." *J. Constr. Eng. Manage.*, 130(3), 405–414.