Optimal Lighting Arrangements for Nighttime Highway Construction Projects

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Abstract: This paper presents a decision support system for optimizing temporary lighting arrangements in nighttime highway construction projects. The system is developed as a multiobjective genetic algorithm that is capable of: (1) maximizing average illuminance on construction sites; (2) maximizing lighting uniformity in the work zone; (3) minimizing glare to workers and road users; and (4) minimizing lighting costs. The system is designed to support decision makers in their search for practical lighting arrangements that provide various tradeoffs among these four conflicting objectives. Five decision variables are optimized in the present system, namely: number of lighting equipment, equipment positioning, mounting height, aiming angle, and rotation angle. The system is also designed to consider and satisfy all practical constraints that can be encountered in this lighting design problem. An application example is analyzed to illustrate the use of the system and demonstrate its capabilities in generating near optimal and practical lighting arrangements for nighttime highway construction projects.

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Introduction

An increasing number of highway construction and repair projects throughout the United States are being performed during the off-peak nighttime hours to alleviate daytime construction-related traffic congestions (El-Rayes and Hyari 2002). This recent increase in the application of nighttime construction in highway projects can be attributed to many reported advantages including: (1) reduced construction-related congestions and motorist delays during daytime hours (Ellis and Amos 1996); (2) decreased project duration (Hancher and Taylor 2001); (3) minimized adverse economic impacts of traffic congestion on local commerce particularly for shipping and delivery services; (4) decreased pollution from idling vehicles stopped at construction sites (McCall 1999); (5) improved work-zone conditions as reduced traffic volume at night creates an opportunity to enlarge work zones; (6) longer working hours at night; (7) enhanced work conditions in hot climate zones due to lower nighttime temperature (Shepard and Cottrell 1985); (8) faster delivery of material to and from the work zone since traffic conditions are better at night, leading to less idle time for both labor and equipment (Price 1986); and (9) improved equipment utilization when longer and/or multiple shifts are employed at night (Hancher and Taylor 2001).

Despite the above advantages, nighttime construction in highway projects still faces a number of challenges including: (1) decreased levels of safety for both workers and motorists due to inadequate lighting conditions and higher levels of glare during nighttime hours (Shepard and Cottrell 1985; Hancher and Taylor 2001); (2) reduced construction quality and productivity due to insufficient lighting conditions on site; (3) increased cost of nighttime operations due to artificial lighting arrangements, labor premiums and overtime, and additional traffic control devices (Hinze and Carlisle 1990); and (4) adverse impact on neighboring environments due to light trespass and construction noise problems resulting from nighttime work (Shepard and Cottrel 1985).

In order to overcome many of the above challenges, proper and adequate lighting arrangements need to be provided on nighttime construction sites. Lighting was reported to be one of the most important factors affecting safety, quality, productivity, and cost of nighttime construction projects (Kumar 1994). The design of lighting arrangements needs to be performed in a systematic and optimal way to achieve the best use of available lighting equipment. Despite the significant research advancements made in the area of optimizing resource utilization in construction (Moselhi and El-Rayes 1993; Hegazy and Elbeltagi 1999; Feng et al. 2000; El-Rayes 2001; El-Rayes and Moselhi 2001; Gomar et al. 2002), there has been little or no reported research on optimizing lighting conditions in nighttime construction projects.

This paper presents an automated decision support system for optimizing the utilization of lighting equipment in nighttime highway construction operations. The system provides support for highway contractors and resident engineers in generating near optimal lighting designs for this type of construction. It is also developed as a robust search and optimization tool that provides:

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J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

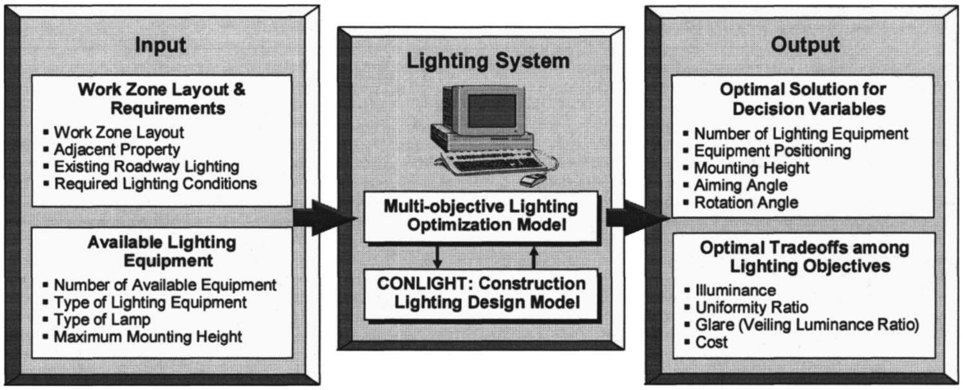

Fig. 1. Lighting decision support system

(1) effectiveness in generating near optimal and practical lighting arrangements; and (2) efficiency in its required computational time and effort for this temporary construction lighting problem.

Lighting Decision Support System

A decision support system is developed to optimize the design of temporary lighting arrangements in nighttime highway construction projects. As shown in Fig. 1, the system accepts readily available input data on nighttime work zone layout and available lighting equipment, and produces optimal lighting arrangements. In order to achieve this, the lighting system incorporates: (1) a multiobjective optimization model; and (2) a construction lighting design model named *CONLIGHT* as shown in Fig. 1. The purpose of the multiobjective optimization model is to search for and identify near optimal lighting arrangements, while the objective of *CONLIGHT* is to evaluate the fitness functions for each of the analyzed lighting arrangements. This paper focuses on the development of the multiobjective optimization model while the detailed development and validation of the lighting design model is described in El-Rayes and Hyari (2005). The present multiobjective optimization model is developed in three main stages: (1) investigating and determining all relevant decision variables and constraints that affect lighting conditions in nighttime highway construction projects; (2) formulating the optimization objectives in this problem; and (3) implementing a robust optimization model that provides the required effectiveness and efficiency for this lighting problem.

Lighting Desicion Variables

Several field studies and a comprehensive literature review were conducted to investigate relevant decision variables that have an impact on lighting conditions in nighttime highway construction projects (El-Rayes et al. 2003). This investigation led to identifying the following five major decision variables as shown in Fig. 2:

1. Number of lighting equipment (K): The designer needs to decide on the number and type of lighting equipment to be used on site. Available alternatives of nighttime lighting equipment include: (1) ground mounted lighting towers; (2) trailer mounted towers; and/or (3) equipment mounted luminaries. Each of this equipment can be supplied with different types of lamps (e.g., metal halide and high pressure sodium vapor lamps) that have varying lamp lumen output (IESNA 1998).
2. Lighting equipment positioning (X_k, Y_k): This variable depicts the horizontal location of lighting equipment k in the work zone in terms of its coordinates (see Fig. 2). The positioning of equipment affects the average illuminance and uniformity of lighting in the work zone.
3. Luminaires mounting height (h): The mounting height represents the vertical distance between the center of the luminaries and the pavement surface as shown in Fig. 2. Portable lighting towers are typically manufactured with adjustable mounting heights that can reach up to 9.14 m (30 ft).
4. Luminaires aiming angle (ω): This denotes the vertical angle between the center of the luminaires beam spread and the nadir, and it affects the coverage area as well as the glare produced by the luminaires as shown in Fig. 2.
5. Luminaires rotation angle (π): This variable represents the rotation of luminaires around a vertical axis (see Fig. 2). A proper rotation angle enables the designer to direct lighting intensity towards the intended area and to minimize light spillage to unnecessary directions, reducing glare and light trespass which are common sources of complaints in nighttime construction especially in urban areas.

Lighting Objectives

The primary goal of nighttime lighting is to provide the best possible visual environment for nighttime construction activities and to minimize negative impact of lighting on road users and workers in a cost-effective manner. To this end, available nighttime lighting standards in various state Departments of Transportation seek to maximize average illuminance and lighting uniformity in the work area while keeping glare levels in and around the site under control (El-Rayes et al. 2003). As such, the present lighting system is designed to enable the simultaneous optimization of four major objectives: (1) maximize average illuminance; (2) maximize lighting uniformity; (3) minimize glare; and (4) minimize lighting costs, as shown in Fig. 1.

1. Maximize Illuminance: The lighting system needs to maximize the average illuminance level (E_{avg}) in the construction work zone. As shown in Eq. (1), an objective function is derived and formulated using the point-by-point method to calculate the average horizontal illuminance in a grid of uniformly distributed points covering the work zone area

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

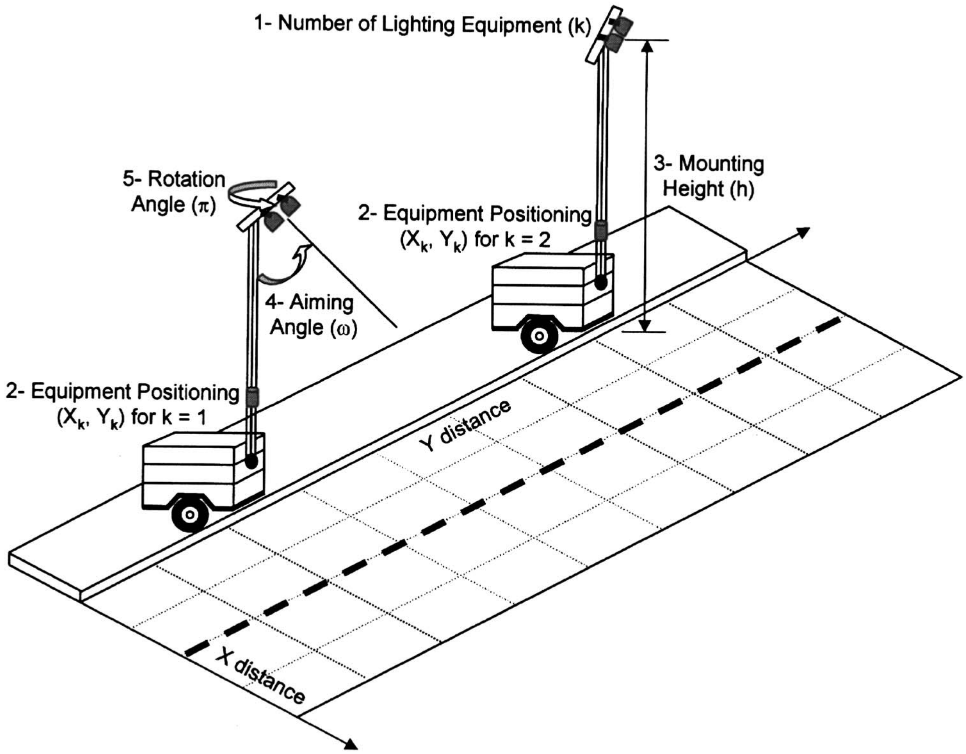

Fig. 2. Lighting decision variables in nighttime construction

considering all light sources in the work zone. In this function, the horizontal illuminance (E_{pk}) at a point p produced by a light source k is calculated using the inverse square law (Pritchard 1995)

$$\text{maximize average illuminance} = E_{avg} = \frac{\sum_{p=1}^{P} \sum_{k=1}^{K} E_{pk}}{P} \tag{1}$$

where E_{avg}=average illuminance level in the work zone; E_{pk}=horizontal illuminance at point p from luminaire k; P=total number of grid points in the studied area; and K=total number of lighting equipment used in design.

2. Maximize lighting uniformity: Light uniformity needs to be maximized to ensure that light is uniformly distributed in all construction areas, and to minimize dark spots in the work zone. This can be achieved by minimizing the uniformity ratio, which represents the ratio of average horizontal illuminance in the work site to the minimum horizontal illuminance computed at any grid point in the work zone (IESNA 2000) as shown in Eq. (2). It should be noted that lighting uniformity improves on site as the uniformity ratio approaches 1, which indicates a smaller difference between the darkest point and the average illuminance in the work zone

$$\text{minimize uniformity ratio} = \frac{E_{avg}}{E_{min}} \tag{2}$$

where E_{avg}=average illuminance in the work area, calculated in Eq. (1); and E_{min}=minimum illuminance level in all grid points.

3 Minimize glare: Glare needs to be minimized in order to limit the visual impairments and/or discomfort experienced by the traveling public and workers. In roadway lighting, the ratio of the maximum veiling luminance to the average pavement luminance is used as a control measure of glare (IESNA 2000). Similarly, the lighting decision support system attempts to minimize this ratio to control glare in nighttime highway construction as shown in Eq. (3). It should be pointed out that the veiling luminance calculations in this system are formulated by adopting the same standard conditions for observer's location and line of sight as those used in roadway lighting design due to the similarity of these conditions in both cases.

$$\text{minimize veiling luminance ratio} = \frac{\text{Max} \sum_{k=1}^{K} (L_v)_{ok}}{L_{avg}} \tag{3}$$

where $\max \Sigma_{k=1}^{K} (L_v)_{ok}$=maximum veiling luminance (i.e., disability glare) value computed at the observer point o from all contributing luminaries $k=1-K$ (IESNA 2000); and L_{avg}=average pavement luminance produced by all lighting sources.

4 Lighting cost: The cost of lighting systems can be reduced by minimizing two major cost items: (1) ownership cost of the lighting equipment, which is either the cost to buy, rent, or lease the equipment; and (2) operational cost, which is a function of the energy consumption and maintenance cost of the lighting equipment

$$\text{minimize cost} = \sum_{k=1}^{K} C_k + R_k \tag{4}$$

where C_k=daily ownership cost of lighting equipment k in dollars; R_k=daily operational cost of a lighting equipment k

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

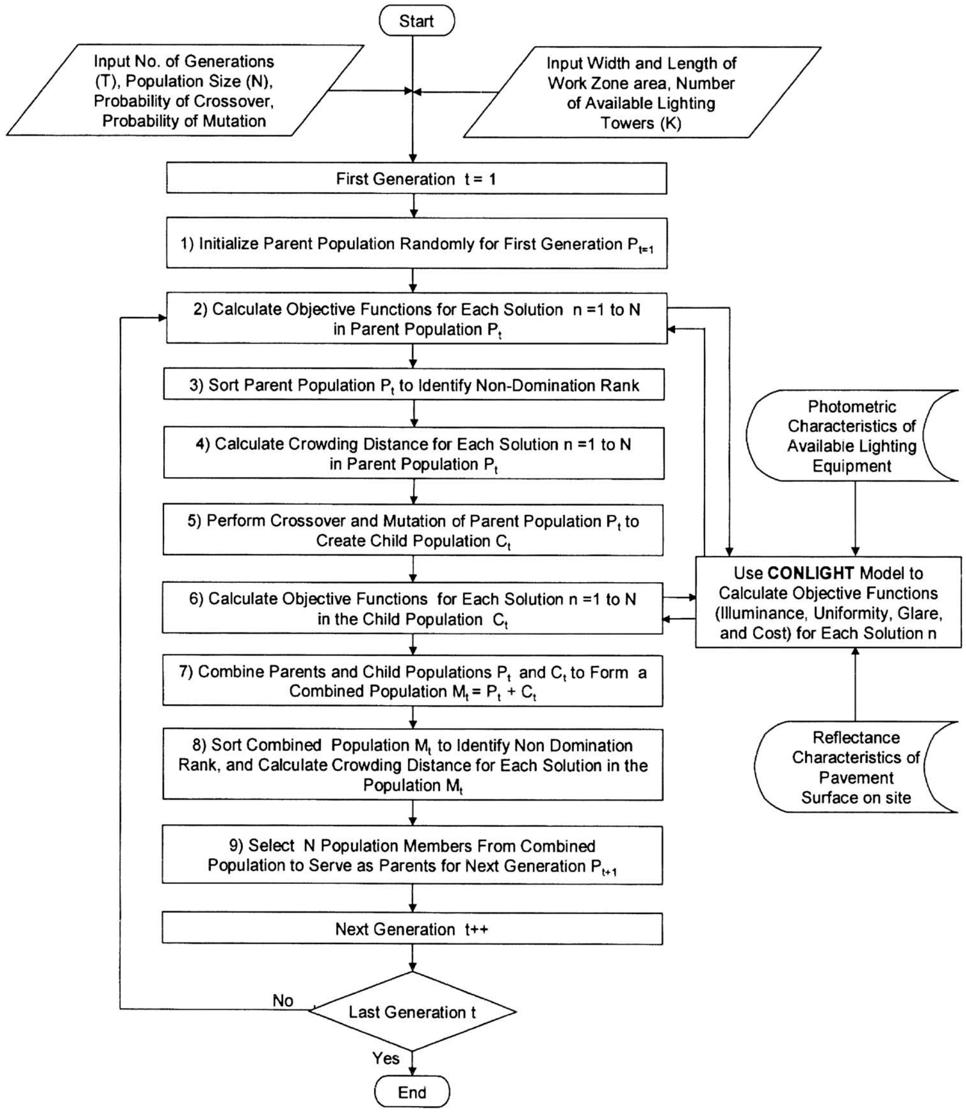

Fig. 3. Multiobjective optimization for construction lighting

in dollars; and K=total number of lighting equipment in the lighting system.

Lighting System Implementation

The lighting decision support system is implemented to consider the above described five decision variables and to optimize the identified four design objectives. In order to enable the optimization of these conflicting objectives, a multiobjective genetic algorithm (GA) is utilized in the development of the system (Deb 2001). Genetic algorithms have been used as an efficient search and optimization tool in a wide variety of construction optimization problems (Feng et al. 1997, 2000; Hegazy 1999; Hegazy and Elbeltagi 1999; Hegazy and Wassef 2001). The GAs are inspired by the mechanics of natural selection and genetics, and therefore they adopt the survival of the fittest and the structured exchange of genetic materials among population members over successive generations as a basic mechanism for the search process (Goldberg 1989).

Similarly, the multiobjective GA used in the development of the lighting decision support system adopts the survival of the fittest approach in addition to the concept of Pareto optimality (Deb 2001), which directs the genetic algorithm to converge to a set of nondominated optimal solutions that represent various tradeoffs among the multiple optimization objectives. In the present optimization problem, this set of nondominated optimal solutions is obtained by: (1) generating an initial set of N possible solutions which constitutes the population of the first generation; and (2) evolving this population of N solutions over T successive generations in order to reach a set of near optimal solutions for this multiobjective optimization problem in a similar process to that adopted by genetic algorithms (Goldberg 1989). This process is performed in nine major cyclic steps (see Fig. 3) as follows:

1. Generate an initial set of N possible solutions for this lighting problem, where each solution provides a possible lighting arrangement for the nighttime construction site (see Fig. 4). The first generation $t=1$ includes N possible solutions and is obtained by generating random values for each of the identified five decision variables using a flexible GA string. As shown in Fig. 4, the length of this GA string depends on the number of lighting equipment K, and accordingly its length is equal to $(2K+10)$. In order to enable the consideration of a wide range of nighttime work zones, the present system is

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

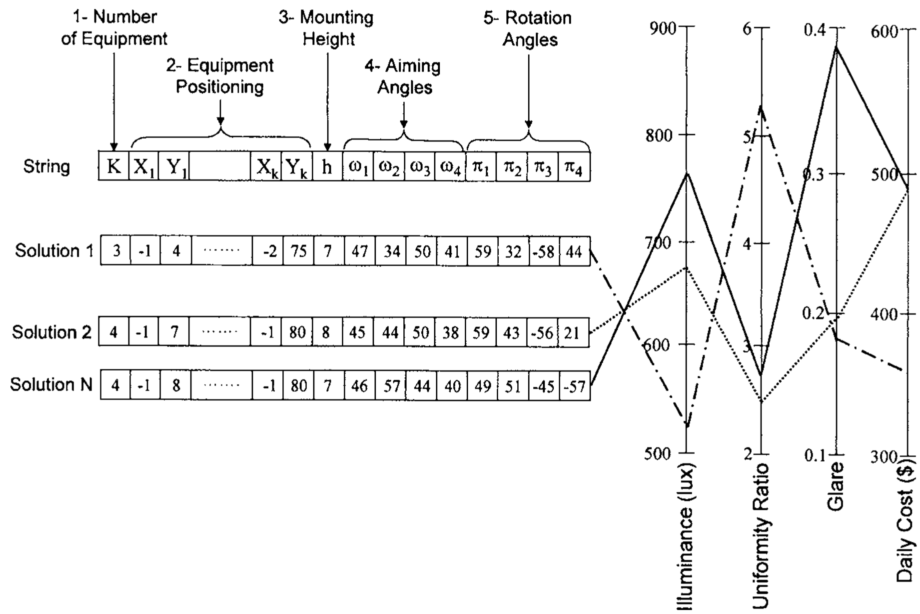

Fig. 4. Possible solutions for lighting arrangements

designed to enable the optimization of up to 20 lighting towers simultaneously. The present system is also flexible and can easily accommodate longer string lengths to enable the optimization of more than 20 lighting towers, if need be. Such expansion in the string length, however, would lead to an increase in the GA computational time, as a longer GA string length typically requires an increase in the analyzed population size (N) and number of generations (T) to ensure the quality of the generated optimal solutions.

2. Calculate the values of the objective functions (i.e., illuminance, uniformity ratio, veiling luminance ratio, and cost) for each solution $n=1-N$ generated in step (1), using a recently developed and validated lighting design model for nighttime construction named *CONLIGHT*. The lighting design model provides the capability of measuring the impact of various lighting arrangements on the earlier described four objective functions in order to ensure that: (1) illuminance levels on site are adequate for all planned nighttime construction tasks; (2) uniformity of light is evenly distributed in all parts of the work area; (3) glare levels are controlled in and around the nighttime construction site; and (4) the cost of nighttime lighting equipment is minimized (El-Rayes and Hyari 2005). As shown in Fig. 3, *CONLIGHT* is capable of calculating these four lighting performance metrics using: (1) the photometric characteristics of available lighting equipment (e.g., light distribution and lamp lumen output for available luminaires); and (2) reflectance characteristics of pavement surface in the work zone. The present decision support system is also designed to consider and satisfy any practical constraints that may be imposed on this optimization problem, and therefore it allows the user to specify the minimum requirements for lighting level, the maximum allowable uniformity ratio, and veiling luminance ratio that should be satisfied by the lighting system. The system ensures that all these practical constraints are satisfied in the generated solution for this problem.

3. Sort all the solutions in the initial population generated in the first cycle or the parent population produced in subsequent cycles P_t in order to identify the degree and rank of nondomination for each solution. A solution is set to be nondominated if there is no other solution that has better values for all the considered objective functions. For example in Fig. 5, solution S_{1c} is nondominated because it is not possible to find another solution that provides higher illuminance and lower glare simultaneously. Similarly, solutions S_{1a}, S_{1b}, S_{1c}, S_{1d}, S_{1e}, and S_{1f} are all considered to be equally nondominated solutions, since each provides a unique and nondominated tradeoff between the two considered objectives in this example (i.e., illuminance and glare). This set of solutions is therefore assigned Rank 1, and are temporarily set aside to enable the ranking of the remaining solutions in a similar process. This leads to the assignment of nondomination Rank 2 to solutions S_{2g}, S_{2h}, S_{2i}, S_{2j}, and S_{2k}, as shown in Fig. 5. This process continues until all population individuals are ranked to represent their degree of nondomination. Ranking of population individuals represents the fitness that will be used as a major criterion in the selection and survival of solutions over successive generations, where solutions with a better rank have a higher possibility of being selected for reproduction (Coello 1999; Deb 2001).

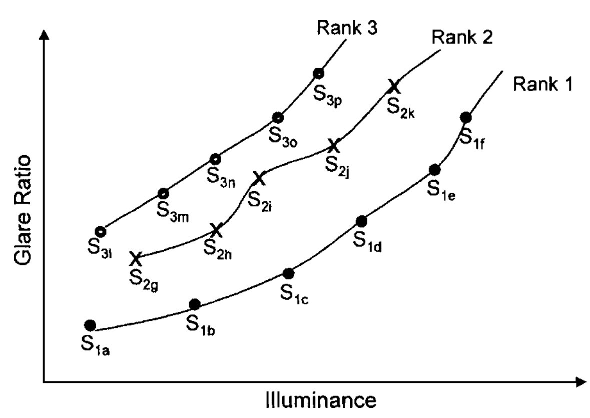

Fig. 5. Ranking of nondominated solutions

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

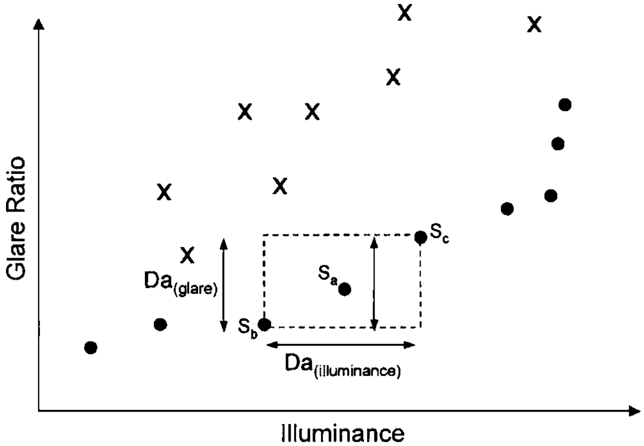

Fig. 6. Crowding distance between solutions

4. Calculate crowding distance for each solution $n=1-N$ in the parent population P_t in order to avoid crowding the solutions in a local region in the search space. This process is intended to favor the spread of the nondominated solutions over the entire space to maintain diversity in the provided solution. The crowding distance is used in the selection process, where the selection probability favors solutions with higher crowding distance if both solutions have the same nondomination rank to decide the winner in tournament selection (Deb 2001). For each solution point, the crowding distance can be calculated by averaging the distance between the two adjacent points in the solution space. As shown in Fig. 6, the crowding distance for solution (a) can be calculated by averaging the distance between points (b) and (c) for each of the two optimization objectives considered in the example shown. Similarly, the crowding distance for each solution is calculated in this four-dimensional optimization model as follows:

$$\text{crowding distance for solution (a)} = \frac{Da_{\text{illuminance}} + Da_{\text{uniformity}} + Da_{\text{glare}} + Da_{\text{cost}}}{4} \qquad (5)$$

5. Perform crossover and mutation of solutions in parent population P_t to create a new child population C_t that contains N new solutions. This process starts by selecting pairs of solutions from the parent population that will be allowed to move to the reproduction phase in order to create a child population. This selection process is performed using a probabilistic approach that favors solutions with better rank, crowding distance, and constraint satisfaction. Each pair of the selected population members is mated to produce new solutions in the child population, using crossover and mutation operators. First, a single point crossover is used, at a randomly chosen cutting point in the two strings, to swap a chunk of the genetic material from the first string with another chunk from the second. Second, a mutation operator is used to change the genetic materials in the strings randomly. This operator is intended to maintain diversity in the population to prevent immature convergence to inferior solutions. Mutation probability is usually small to ensure that this operator will not have a disruptive effect on the best members of the population (Goldberg 1989).
6. Evaluate fitness functions for each solution $n=1-N$ in the newly created child population C_t in a similar process to that described in step (2).
7. Combine child and parent populations (C_t and P_t) to form newly combined population $M_t=P_t+C_t$, with a double population size of $2N$.
8. Sort the solutions in the combined population M_t in order to identify: (1) the rank of nondomination and (2) crowding distance for each solution, using a similar process to that earlier described in steps (3) and (4), respectively.
9. Select a new parent population for the next generation by selecting the best 50% members of the combined population M_t according to their nondomination rank followed by their crowding distance. This process can be considered as a strong form of elitism as it enables preserving the best members of the parents' population over generations (Deb 2001).

The above computation steps of (2)–(9) are repeated over a number of specified generations ($t=1-T$) in order to yield a set of nondominated solutions for the lighting optimization problem. Each solution in this optimal set represents a lighting arrangement that provides a unique tradeoff among the lighting objectives. The decision maker can select, from this set, the best overall arrangement that satisfies the requirements of the nighttime construction site being considered.

Application Example

An application example is analyzed to illustrate the capabilities of the present system in generating near optimal lighting arrangements for a typical nighttime work zone in a two-lane road. The work zone extends to a distance of 90 m, and is required to be illuminated in both lanes simultaneously to avoid moving lighting equipment when work shifts from one lane to the other. This particular work zone size was identified as a practical and representative example after: (1) conducting a number of site visits to nighttime construction projects; and (2) consulting with operation engineers in the Illinois Department of Transportation, who recommended the testing of a modular two-lane work zone length that requires the utilization of at least three light towers: two exterior at both ends of the area and one interior at the middle of the area (El-Rayes et al. 2003; Hyari 2004). The middle section of this modular work zone is primarily illuminated by the interior tower in addition to secondary contributions from the two adjacent exterior towers on both sides. As such, this middle area of the work zone represents a modular section that can be repeated as much as needed between the two exterior towers in longer work zones that exceed the analyzed 90 m length in this example.

The lighting requirements that should be satisfied in this example are: (1) a minimum average horizontal illuminance level of 216 lx; (2) a maximum allowed uniformity ratio of 6; and (3) a maximum allowed glare (veiling luminance ratio) of 0.4, as recommended by available Department of Transportation (DOT) lighting standards (El-Rayes et al. 2003). The contractor plans to rent typical trailer mounted light towers that are equipped with four 1000 metal halide luminaries at a daily rental and operational cost of \$120/tower. The objectives of the lighting design in this example are: (1) maximize average illuminance to provide improved visibility for the construction activities in the work zone; (2) minimize uniformity ratio to ensure uniform distribution of light on site; (3) minimize glare to control its negative impact on workers and road users alike; and (4) minimize total cost of lighting equipment. Optimizing these four conflicting objectives is a challenging design task that requires evaluating the performance

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

Table 1. Sample Solutions for Lighting Arrangements

	Lighting decision variables																Lighting objectives			
Solution n	Number of lighting equipment K	Lighting equipment positioning (X_k,[a] Y_k[b]) $k=1$	$k=2$	$K=3$	$k=4$	$k=5$	Mounting height h (m)	Aiming angles for 4 lm ω (1)	(2)	(3)	(4)	Rotation angles for 4 lm π[c] (1)	(2)	(3)	(4)	Illuminance (lx)	Lighting uniformity ratio	Glare (veiling luminance ratio)	Daily cost ($)
1	3	(−1,4)	(−2,40)	(−2,75)	—	—	7	47	34	50	41	59	32	−58	44	534.5	5.28	0.189	360
2	3	(−1,5)	(−2,40)	(−2,75)	—	—	8	48	36	49	42	59	51	−54	43	518.9	3.97	0.205	360
3	3	(−1,8)	(−2,40)	(−2,75)	—	—	8	56	36	50	43	59	51	−54	43	520.0	3.78	0.301	360
4	3	(−1,8)	(−2,42)	(−2,75)	—	—	6	48	36	51	58	60	51	−54	43	590.5	5.07	0.396	360
5	4	(−1,7)	(−2,37)	(−1,58)	(−3,89)	—	8	45	35	46	41	59	14	−46	44	571.7	4.02	0.152	480
6	4	(−1,7)	(−2,34)	(−1,58)	(−1,80)	—	8	45	44	50	38	59	43	−56	21	668.2	2.51	0.195	480
7	4	(−1,8)	(−2,40)	(−1,59)	(−1,80)	—	8	43	35	46	43	60	51	−54	43	732.8	4.59	0.280	480
8	4	(−1,8)	(−1,35)	(−1,58)	(−1,80)	—	7	46	57	44	40	49	51	−45	−57	761.8	2.66	0.387	480
9	5	(−1,4)	(−5,24)	(−3,36)	(−1,59)	(−4,80)	8	45	25	8	29	27	−57	−38	60	580.0	3.89	0.121	600
10	5	(−3,5)	(−3,26)	(−1,49)	(−5,66)	(−4,82)	8	53	36	33	52	26	−58	−34	55	706.9	2.17	0.166	600
11	5	(−1,8)	(−2,30)	(−4,35)	(−1,59)	(−1,82)	7	46	51	52	51	27	−60	−34	56	868	2.08	0.262	600
12	5	(−1,7)	(−2,29)	(−1,38)	(−1,59)	(−1,82)	6	52	50	44	43	57	47	−31	−59	1,028.5	2.63	0.307	600

[a]X_k value represents transverse distance from the edge of the road, where negative values indicate an outward direction from the road (see Fig. 2).

[b]Y_k value represents longitudinal distance parallel to the edge of road, measured from the start of the work zone (see Fig. 2).

[c]π value represents rotation angle measured from a perpendicular direction to the road, where positive and negative values indicate clockwise and counterclockwise rotations, respectively.

of a large number of lighting arrangements, where each represents one possible combination of the earlier described decision variables (i.e., the number of utilized lighting equipment, equipment positioning, mounting height, aiming angle, and rotation angle) as shown in Fig. 2. The need for optimizing this lighting design was clearly recognized during a number of site visits and field tests that confirmed that the lack of such analysis prior to construction not only leads to inferior lighting conditions on site but often fails to satisfy even the minimum DOTs lighting requirements (El-Rayes et al. 2003; Hyari 2004).

The present system was utilized to search for near optimal lighting arrangements that optimize these four major design objectives simultaneously. As shown in Fig. 1 and Table 1, the system provides the capability of: (1) considering the above described work zone layout and its requirements; and (2) generating a set of near optimal lighting arrangements for this application example that provides feasible tradeoffs among illuminance, uniformity, glare, and cost. A number of these generated lighting arrangements were examined in field experiments in order to enable a comparison between the results provided by the present system and those measured in the field. The results of this validation analysis indicate that there is close agreement between the results provided by the lighting system and those measured on site with an average accuracy of 86% (Hyari 2004; El-Rayes and Hyari 2005).

The generated solutions for this example illustrate a set of optimal tradeoffs among illuminance, uniformity, glare, and cost for the analyzed work zone. Each of these optimal tradeoffs can be achieved on site by setting up the identified lighting arrangement in Table 1. For example, each of the first four arrangements in Table 1 utilizes three light towers and therefore has the same cost; however each leads to a unique tradeoff among the remaining three objectives as a result of varying the location, mounting height, aiming angles, and rotation angles of the luminaries in the three light towers. In these arrangements, solution (4) provides 13.5% higher illuminance than solution (3); however it provides 34 and 32% higher uniformity ratio and glare, respectively.

Since all the generated solutions in Table 1 satisfy all the aforementioned DOT lighting requirements in this example, a decision maker can evaluate the obtained tradeoffs among the four lighting objectives and select an arrangement that best suits the specific requirements of the project being considered. For example, if the highest priority in the project is placed on minimizing cost followed by controlling glare then maximizing illuminance, then the decision maker can select solution (1) in Table 1 and accordingly set up its recommended lighting arrangement on site. Other project priorities can similarly be analyzed in order to select the most appropriate lighting arrangement from the generated set of optimal tradeoffs. In order to facilitate this selection process, the generated tradeoffs among the four objectives can be visualized graphically using: (1) a single four-dimensional (4D) graph that displays the tradeoffs among the four objectives simultaneously, as shown in Fig. 4; and/or (2) multiple two-dimensional (2D) graphs that illustrate the tradeoffs among two objectives at a time, as shown in Figs. 7 and 8.

First, a 4D graph enables the visualization of all objectives simultaneously; however it can be used to view only a limited number of the generated solutions. Second, 2D graphs can present the entire set of generated solutions; however they are capable of illustrating only two lighting objectives at a time. In this example, six 2D graphs are obtained to illustrate all possible combinations of tradeoffs among the four lighting objectives. Figs. 7 and 8 present a sample of these graphs that show illuminance/glare and

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

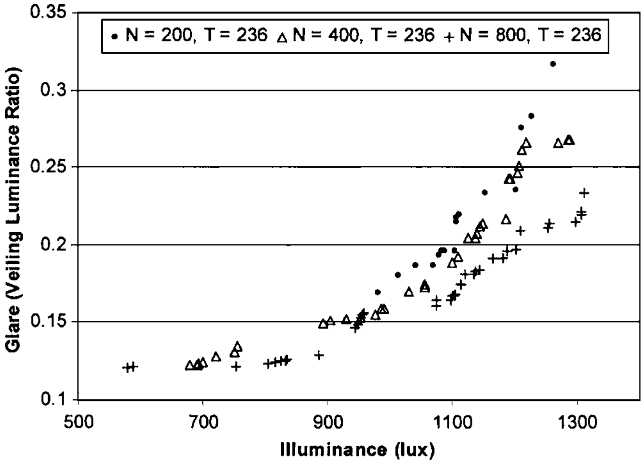

Fig. 7. Illuminance/glare tradeoff analysis

lighting uniformity/glare tradeoffs, respectively. These figures confirm that the identified four lighting objectives conflict with one another, as the improvement in one objective leads to deterioration in the other. The shape of these tradeoffs can help decision makers select a lighting arrangement that provides the best balance among the four objectives. For example, a close analysis of the tradeoff shown in Fig. 8 indicates that lighting arrangement *A* can be preferred over the others because of the fact that it provides: (1) better lighting uniformity than those in group *B*; and (2) better glare than those in group *C*. It can also be shown that any further improvement in uniformity beyond arrangement *A* will cause significant deterioration in glare, as shown in Fig. 8.

Furthermore, several runs were performed to study the impact of varying population sizes on the quality of the obtained solutions in terms of the spread of the solutions over the entire optimal front, and in terms of the performance of the four lighting objectives. The results of this analysis confirm that increasing the population size leads to: (1) improved quality of the solution, as shown in Fig. 7; and (2) higher computational requirements. This tradeoff should be carefully considered in the selection of the population size. In this analysis, it was observed that it was feasible to reduce the computational requirements for this lighting design problem by reducing the population size. As shown in Fig. 7, the run with a population size of 200 provided acceptable results compared to that with a population size of 800. The number of function evaluations in the former run with a reduced population size is one quarter of that in the run with a population size of 800. A decision maker can evaluate this tradeoff between computational requirements and solution quality, and select a population size that satisfies the specific requirements of the project being analyzed.

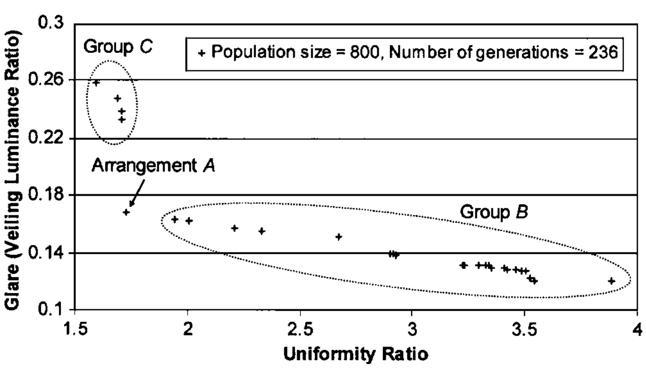

Fig. 8. Lighting uniformity/glare tradeoff analysis

Conclusion

A multiobjective decision support system was developed to optimize lighting conditions for nighttime highway construction operations. The system is designed to search for near optimal lighting arrangements that maximize illuminance and lighting uniformity in the work zone, while minimizing glare and lighting costs. The system is developed in three main stages: (1) incorporating all relevant decision variables and constraints that affect lighting conditions in nighttime highway construction projects; (2) formulating the optimization objectives in this design problem; and (3) implementing the system as a robust design tool that provides the required effectiveness and efficiency for this particular domain. The system provides a number of practical capabilities, including: (1) enabling the optimization of multiple and conflicting lighting objectives; (2) generating practical lighting arrangements that provide various tradeoffs among the identified optimization objectives; (3) quantifying glare which is a major source of complaints in this type of construction; (4) incorporating cost as an important objective in the optimization of lighting arrangements; and (5) satisfying all practical constraints that can be encountered in this lighting design problem. These capabilities enable decision makers to generate and implement near optimal lighting arrangements that can lead to significant improvements in safety, quality, productivity, and cost effectiveness in nighttime highway construction projects.

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Notation

The following symbols are used in this paper:

C_k = daily ownership cost of lighting equipment k in dollars;
C_t = child population in generation t;
E_{avg} = average illuminance level in work zone;
E_{min} = minimum illuminance level in all grid points;
E_{pk} = horizontal illuminance at point p from luminaire k;
h = luminaires mounting height;
L_{avg} = average pavement luminance level produced by all lighting sources;
$(L_v)_{ok}$ = maximum veiling luminance (i.e., disability glare) value computed at observer point o from all contributing luminaries $k=1$ to K (IESNA 2000);
M_t = combined parents and child population in generation t;
P_t = parent population in generation t;

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300

R_k = daily operational cost of lighting equipment k in dollars;

(X_k, Y_k) = lighting equipment positioning;

π = luminaires rotation angle; and

ω = luminaires aiming angle.

Subscripts and Superscripts

k = lighting equipment (from $k=1$ to K);

n = solution (from $n=1$ to N);

o = observer point;

p = grid point (from $p=1$ to P); and

t = generation (from $t=1$ to T).

References

Coello, C. (1999). "A comprehensive survey of evolutionary-based multi objective optimization techniques." Laboratorio Nacional de Informatica Avanzada, Veracruz, Mexico http://www.lania.mx/~ccoello

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms*, Wiley, New York.

Ellis, R. D. Jr., and Amos, S. J. (1996). "Development of work zone lighting standards for nighttime highway work." *Transportation Research Record*, *1529*, Transportation Research Board, Washington D.C.

El-Rayes, K. (2001). "Optimum planning of highway construction under the $A+B$ bidding method." *J. Constr. Eng. Manage.*, 127(4), 261–269.

El-Rayes, K., and Hyari, K. (2002). "Automated DSS for lighting design of nighttime operations in highway construction projects." *Proc., 19th International Symp. on Automation and Robotics in Construction, ISARC 2002*, National Institute of Standards and Technology, Washington, D.C.

El-Rayes, K., and Hyari, K. (2005). "CONLIGHT: Lighting design model for nighttime highway construction." *J. Constr. Eng. Manage.*, 131(4), 467–476.

El-Rayes, K., Liu, L., Soibelman, L., and Hyari, K. (2003). "Nighttime construction: Evaluation of lighting for highway construction operations in Illinois." *Final Rep. Project No. VD-H1, FY 00/01, ITRC FR 00/01-2*, Illinois Transportation Research Center, Illinois Department of Transportation, Ill.

El-Rayes, K., and Moselhi, O. (2001). "Optimizing resource utilization for repetitive construction projects." *J. Constr. Eng. Manage.*, 127(1), 18–27.

Feng, C. W., Liu, L., and Burns, S. (1997). "Using genetic algorithms to solve construction time-cost trade-off problems." *J. Comput. Civ. Eng.*, 11(3), 184–189.

Feng, C. W., Liu, L., and Burns, S. (2000). "Stochastic construction time-cost trade-off analysis." *J. Comput. Civ. Eng.*, 14(2), 117–126.

Goldberg, D. (1989). *Genetic algorithms in search, optimization, and machine learning*, Addison Wesley Longman, Inc., Reading, Mass.

Gomar, J., Haas, C., and Morton, D. (2002). "Assignment and allocation optimization of partially multiskilled workforce." *J. Constr. Eng. Manage.*, 128(2), 103–109.

Hancher, D., and Taylor, T. (2001). "Night-time construction issues." *Proc., Transportation Research Board 80th Annual Meeting*, Washington, D.C.

Hegazy, T. (1999). "Optimization of resource allocation and leveling using genetic algorithms." *J. Constr. Eng. Manage.*, 125(3), 167–175.

Hegazy, T., and Elbeltagi, E. (1999). "EvoSite: Evolution-based model for site layout planning." *J. Comput. Civ. Eng.*, 13(3), 198–206.

Hegazy, T., and Wassef, N. (2001). "Cost optimization in projects with repetitive nonserial activities." *J. Constr. Eng. Manage.*, 127(3), 183–191.

Hinze, J., and Carlisle, D. (1990). "Variables impacted by nighttime construction projects." *Final Rep. No. TNW 90-07*, Transportation Northwest, Univ. of Washington, Seattle, Wash.

Hyari, K. (2004). "Optimizing lighting conditions for nighttime highway construction operations." PhD dissertation, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.

Illumination Engineering Society of North America (IESNA). (1998). "IESNA guide for choosing light sources for general lighting." *Rep. No. DG-10-98*, New York.

Illuminating Engineering Society of North America (IESNA). (2000). "IESNA practice for roadway lighting." *Rep. No. ANSI/IESNA RP-8-00*, American National Standard, New York.

Kumar, A. (1994). "Development of a model for determining work zone illumination requirements during nighttime highway construction." PhD dissertation, Univ. of Florida, Gainesville, Fla.

McCall, H. C. (1999). "Report on the Department of Transportation's Administration of the Nighttime Construction Program." *Rep. No. 98-S-50*, State of New York Office of the State Comptroller, Albany, N.Y.

Moselhi, O., and El-Rayes, K. (1993). "Scheduling of repetitive projects with cost optimization." *J. Constr. Eng. Manage.*, 119(4), 681–697.

Price, D. A. (1986). "Nighttime paving." *Implementation Rep. No. CDOH/DTP/R-86/6*, Colorado Dept. of Highways, Federal Highway Administration, Denver.

Shepard, F. D., and Cottrel, B. (1985). "Benefits and safety impact of night work-zone activities." *Rep. No. FHWA/RD-85/067*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Pritchard, D. C. (1995). *Lighting*, 5th Ed., Longman Scientific and Technical, Burnt Mill, Harlow, Essex, United Kingdom.

J. Constr. Eng. Manage., 2005, 131(12): 1292-1300