Linear Programming Approach to Optimize Strategic Investment in the Construction Workforce

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Abstract: The construction industry in the United States and other parts of the world has been facing several challenges, including a shortage of skilled workers. A review of the relevant body of knowledge indicates that one of the key reasons for this problem is the absence of human resource management strategies for construction workers at project, corporate, regional, or industry levels. This paper addresses the issues of workforce training and allocation on construction projects. It presents a framework to optimize the investment in, and to make the best use of, the available workforce with the intent to reduce project costs and improve schedule performance. A linear program model, entitled the Optimal Workforce Investment Model, is built to provide an optimization-based framework for matching supply and demand of construction labor most efficiently through training, recruitment, and allocation. Given a project schedule or demand profile and the available pool of workers, the suggested model provides human resource managers a combined strategy for training the available workers and hiring additional workers. The input data to the proposed model consists of a certain available labor pool, cost figures for training workers in different skills, the cost of hiring workers, hourly labor wages, and estimates of affinities between the different considered skills. The objective of the model is to minimize labor costs while satisfying project labor demands. Results from application of the model to typical situations are presented, and recommendations for future developments are made.

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Introduction

The construction industry is facing a skilled labor shortage in all trades over all regions of the United States. A report issued by the Construction Users Round Table (CURT 2001) attributes the problem to several factors including poor retention, poor training, and relatively low wages. Tucker et al. (1999) attribute the problem to other factors such as the generally poor image of the industry, a working environment that is considered undesirable, the transient nature of the work, and the resulting unclear career paths in construction. Emerging initiatives to address this problem include craft and supervisory training, multiskilling, and self-directed work teams as well as productivity enhancements utilizing technology, constructability, and prefabrication. Efforts to quantify or qualify the resulting benefits, however, have been unsatisfactory. Much of the workforce remains unskilled or underskilled, therefore training must be considered as an option when staffing for a project.

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This study provides an optimization-based framework for matching supply and demand of construction labor most efficiently through training, recruitment, and allocation. Given a project schedule or demand profile and the available pool of workers, the suggested model provides human resource managers a combined strategy for training the available workers and hiring additional workers. The objective of the model is to minimize labor costs while satisfying project labor demands. Future work will extend the model in several directions.

Skilled Labor Shortage in Construction Industry

Background

The problem of skilled labor shortage in the United States construction industry was predicted more than 2 decades ago. A report written by the Business Round Table (BRT 1983) described a skilled labor shortage as one of the main challenges the United States Construction industry would be facing in the last decade of the past century. The report predicted shortages of construction labor in both the open-shop environment and the union environment due to contractors' lack of interest in training and owners' ignorance.

A more recent study by the Construction User Round Table (CURT 2001) showed that owner companies considered the shortage of skilled labor as the most critical problem today's construction industry is facing. Of the responding companies, 82% experienced shortages of skilled workers on their projects. Within the same sample, 78% indicated that the trend has worsened over the past few years. Finally, 73% described the impact on projects as "moderate to significant." The study found that all types of construction projects (i.e., all sizes, all areas, and in every craft) are affected by shortages; however, the most affected crafts were electricians, pipe fitters, and welders.

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Recent statistics published by the Bureau of Labor Statistics (BLS 2004) indicate that by 2010, there will be a need to replace 1,469,000 construction trade worker jobs. The recent BLS data indicate that the construction industry is projected to be the largest and fastest source of employment growth among goods-producing industries. For example, demand for sheet-metal workers is expected to have the fastest growth among other trades, adding 43,400 new jobs. Another fast-growing occupation is electricians, which will experience demand for 84,800 jobs. Finally, the demand for construction laborers is expected to increase by 106,480 by 2010. Given this projected growth in the need for skilled construction workers and the poor image of the industry, construction employers might face problems finding new entrants to fill these positions, or finding entrants with all the necessary skills.

The skilled labor shortage extends beyond the United States. The construction industry in the United Kingdom for example is facing a skilled labor shortage (Mackenzie et al. 2000). The United Kingdom construction industry must draw from all labor sources irrespective of construction-related experience, age, gender, ethnic, or social background. A study of infrastructure in South Africa revealed a shortage of individuals to build and maintain infrastructure in underdeveloped areas (Philips et al. 1995). A study of railways in Japan linked the reduction in maintenance of the existing lines to the problem of labor shortages (Tarumi 1994). The recent annual outlook by the construction workforce development forecasting committee (CWDFC) of the Construction Owners Association of Alberta (COAA) reported shortages in some construction trades in Alberta, Canada. Six trades faced shortages in 2002. These are: boilermakers, electricians, carpenters, bricklayers, insulators, and plumbers/pipe fitters.

Previous Solutions

Several solutions have been used to alleviate the problem of skilled labor shortages in construction. These include increased wages and other incentives such as guaranteed overtime, implementation of training incentives, employing foreign labor or even outsourcing construction work to foreign sources, and reduction of demand through automation and technology (Pappas 2004). However, such measures are difficult to sustain unless backed by a long-term strategy to support them.

A recent collaboration between the Construction Industry Institute (CII) and the Center for Construction Industry Studies (CCIS) at the University of Texas at Austin produced a theoretical model for a revolutionary way to address the issue in a more comprehensive manner. Although the method, called "Tier II," is new and future oriented, it may have a considerable impact on the construction workforce and industry (Castaneda 2002). The proposed Tier II strategy calls for training workers possibly in more than one skill, including management and other soft skills. This document focuses on the implementation of one of the main elements of the Tier II strategy, namely how to improve workers' skill sets. The main objective is to provide a framework for making the best use of the available workforce and its skills set using an optimization-based approach.

The use of optimization techniques is not limited to the construction industry. Optimization is a concept that has been extensively used in different fields such as communication, transportation, health care, manufacturing, finance, and others. Shift scheduling is a classical problem in a variety of service organizations such as airlines, law enforcement, hotels, postal service, banks, hospitals, and telecommunication companies. The problem typically involves meeting a certain demand pattern which often changes over the course of an operating day or week. The solution of the problem usually provides the assignment of employees to various shifts that are specified by shift type, length, start time, and the number and length of breaks (Aykin 1996). Early attempts to tackle this problem include Edie (1954) and Dantzig (1954), who provided a set-covering formulation.

There is a renewed emphasis on employee development in the United States, especially in the manufacturing arena. The adoption of newer forms of manufacturing organizations often calls for additional training and/or cross training of employees. As described by Stewart et al. (1994): "decisions of whom to train and how much training should be done are often made in a qualitative fashion by human resource or personnel managers."

The need for mathematical programming techniques to optimize strategic investment in the construction workforce has been noted in several studies (Burleson et al. 1998; Gann and Senker 1998; and Gomar et al. 2002). Burleson et al. (1998) studied four multiskilling strategies (dual-skill, four-craft, four-craft-helper, theoretical maximum) on a hypothetical petro-chemical processing facility and recommended developing an automated analysis process to determine optimal multiskilling strategies.

Gomar et al. (2002) acknowledged this need and developed a model capable of optimizing the labor allocation and assignment process of a partially multiskilled workforce and a single-skilled workforce with the multiple objectives of minimizing hires, maximizing employee duration on project, and minimizing reallocation within the project. The model which provides the number of workers within the different crafts to hire over time was applied to the CII model plant—a detailed description of a hypothetical project developed by CII member companies. A sample of 10 days was taken from the project schedule. The model ensured demand is satisfied using a workforce supply of 20 workers, mostly multiskilled. Gomar et al. recognized the need for having models that can solve problems with more than 20 workers over a period of time longer than 20 days. They also recommended running tests with different skill combinations that represent natural affinities in order to determine the most effective combinations.

In another study which mentions the need for a multiskilled workforce to optimize the use of construction labor, Gann and Senker (1998) claim that versatile multiskilled employees are needed increasingly, especially in repair and maintenance work. Maintenance employees need to be multiskilled to enable them to deal with mechanical, electrical and electronic control equipment.

This study uses mathematical modeling techniques to provide a strategy to work within the constraints of the ongoing construction labor shortage situation. It provides an optimal investment strategy for construction companies in their workforce. Given a project schedule and the available worker pool, the optimal workforce investment model (OWIM) provides human resource managers a training strategy for the available workers as well as a strategy for hiring additional workers to minimize labor costs.

Model Formulation

The OWIM was formulated as a linear programming (LP) model. LP is the most widely applied optimization method (Pike 1986). It was developed in 1947 by George Dantzig who recognized a generalization in the mathematics of scheduling and planning problems (Pike 1986). The development of LP has followed the advance in digital computing. Today's algorithms and computers

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have the ability to solve LP models with tens of thousands of decision variables and structural constraints.

Decision Variables

The OWIM includes the following decision variables:

1. x_{ij}=the number of workers who possess only skill i but will be trained in skill j prior to the project's initiation;
2. y_i=the number of workers with only skill i to be hired;
3. z_{ij}=the number of workers possessing skills i and j to be hired;
4. l_{ijt}=the number of workers possessing skills i and j (i not equal to j) working in their primary skill i during time period t. This paper assumes that workers possessing skills i and j can perform work equally in either of their two skills. The notation of "primary" and "secondary" is useful only for the formulation of the model (Srour 2005);
5. m_{ijt}=the number of workers possessing skills i and j working in their secondary skill j during time period t; and
6. n_{it}=the number of workers with skill i working during time period t

The last three decision variables in this list are typically used by site management. They represent the worker assignments, i.e., the job they are responsible for on a particular day or time period. The first three decision variables in the list, which consist of the number of workers to hire and the number of workers to train, represent decisions human resources departments make either at a project level or at a corporate level. They also reflect the amount of investment a firm is willing to make in its labor group.

Training can be performed either through an on-the-job mechanism or through a formal approach (Villalobos 1997). During a certain project stage, the worker with the most expertise in a certain craft can assume the role of the mentor and the remaining members of the crew can assume the roles of apprentices or helpers. As pointed out by Maloney and McFillen (1995), the training of apprentices by individual craftsman has been the norm for centuries, prior to the development of union apprenticeship programs and nonunion training programs. Formal training, conversely, is usually performed after hours or on weekends. Training can take the form of structured modules.

Objective Function

The OWIM attempts to minimize the construction labor-related costs incurred in the planning and execution phases of the project, while matching the labor demand profile over the course of the project. The objective function of the OWIM consists of a summation of the following four terms:

1. The cost that will be incurred to train in skill j the workers who already possess skill i

$$\sum_i \sum_j \frac{\text{traincost}_{ij} \times x_{ij}}{\alpha_{ij}}$$

   where traincost_{ij}=cost in United States dollars to train a worker who possesses skill i in skill j. α_{ij}, which will be explained in further detail subsequently in this document,=skill affinity penalty between skills i and j with values ranging between 0 and 1;
2. the cost that will be incurred to hire workers with skill i

$$\sum_i y_i \times \text{hirecost}_i$$

   where hirecost_i=hiring cost in United States dollars of a worker with skill i;
3. the cost that will be incurred to hire workers with skills i and j

$$\sum_i \sum_j z_{ij} \times \text{hcost}_{ij}$$

   where hcost_{ij}=hiring cost in United States dollars of a worker who possesses skills i and j; and
4. The incurred wages on site:
   a. by workers who possess only skill i

$$\sum_i \sum_t n_{it} \times \text{wage}_i \times \text{hrsperweek}$$

   where wage_i=hourly wage in United States dollars of a worker with skill i; hrsperweek=number of weekly hours of work; and t=time period index;
   b. by workers who possess both skills i and j working with skill i during time period t:

$$\sum_i \sum_j \sum_t l_{ijt} \times w_{ij} \times \text{hrsperweek}$$

   where w_{ij}=hourly wage in United States dollars of a worker with skills i and j;
   c. by workers who possess both skills i and j working with skill j during time period t:

$$\sum_i \sum_j \sum_t m_{ijt} \times w_{ij} \times \text{hrsperweek}$$

Constraints

The limiting constraints of the OWIM are as follows:

1. Meeting the demand d_{it} for skill i during time period t using multiskilled workers (possessing skills i and j) and single-skilled workers (possessing skill i)

$$\sum_j l_{ijt} + \sum_j m_{ijt} + n_{it} \geq d_{it}$$

   d_{it} can be obtained from any scheduling software. It consists of the daily demand loading as calculated by P3 based on the project schedule, loading of all project activities with the resource requirements, and leveling the schedule using these resources. This constraint may be interpreted as follows: the number of workers working with skill i during the time period t must be greater than or equal to the demand for workers with skill i during the same time period.
2. Training capacity of skill j

$$\sum_i x_{ij} \leq \text{traincap}_j$$

   The reason for having this set of constraints is that there might be conditions in which there is a limitation on the number of workers that can be trained during a short time. For example, if training is to be performed on the job, there might not be enough workers that can serve as mentors for the trainees. If training is performed in a formal fashion, there might not be enough training centers or facilities.
3. Hiring capacity constraints:

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Objective

$$\min\Big(\sum_i\sum_j \frac{traincost_{ij}}{\alpha_{ij}} \times x_{ij} + \sum_i y_i \times hirecost_i + \sum_i\sum_j z_{ij} \times hcost_{ij}$$
$$+ \sum_i\sum_t n_{it} \times wage_i \times hrsperweek + \sum_i\sum_j\sum_t l_{ijt} \times w_{ij} \times hrsperweek$$
$$+ \sum_i\sum_j\sum_t m_{ijt} \times w_{ij} \times hrsperweek\Big)$$

s.t. $n_{it} \le s_i + y_i - \sum_j x_{ij} \quad \forall i \in I, t \in T$

$l_{ijt} + m_{ijt} \le x_{ij} + z_{ij} + p_{ij} \quad \forall i \in I, j \in I, t \in T$

$\sum_j l_{ijt} + \sum_j m_{jit} + n_{it} \ge d_{it} \quad \forall i \in I, t \in T$

$\sum_i x_{ij} \le traincap_j \quad \forall j \in I$

$y_i \le hirecap_i \quad \forall i \in I$

$z_{ij} \le hcap_{ij} \quad \forall i \in I, j \in I$

$x, y, z, l, m, n \ge 0$

Fig. 1. OWIM formulation

a. $y_i \le \text{hirecap}_i$=number of workers to hire with skill i is limited by a certain number of available workers hirecap_i;

b. $z_{ij} \le \text{hcap}_{ij}$=number of workers to hire with skills i and j is limited by a certain number of available workers hcap_{ij}

This set of constraints is particularly important in cases where the project is in a remote area with limited labor resources. It is also important during periods of labor shortages due to economic conditions or other factors.

4. Availability constraints:

a. $n_{it} \le s_i + y_i - \Sigma_j x_{ij}$=set of constraints which makes sure that the model does not use more workers with skill i during time period t than the available pool, where s_i represents the number of workers with skill i who are already employed by the company.

b. $l_{ijt} + m_{ijt} \le x_{ij} + z_{ij} + p_{ij}$=set of constraints which makes sure that the model does not use more workers working in their primary skill (i) or in their secondary skill (j) during time period t than the available pool, where p_{ij} represents the number of workers with skills i and j who are already employed by the company.

Fig. 1 summarizes the formulated LP model. The developed model is coded in an optimization software entitled GAMS and solved using the CPLEX solver. GAMS permits the expression of optimization problems independently of the data. This separation of logic (or mathematical equations) and data is useful in large and complex problems which may require some revisions before arriving at the final version of the formulated problem. Also, it allows construction contracting firms, which are intended to be the final users of the OWIM, to input their own data to GAMS in the forms of Microsoft Excel tables without having to change any mathematical equations.

Evaluation of Case Studies

This section presents the details of the project to which the OWIM was applied (CII model plant), the assumptions that were made, and other input data to the proposed model. Information on training and hiring costs was gathered from different sources including academic literature and industry data. Finally, the results from the application of the model to five case studies are presented.

Input Data

The CII model plant was developed by CII member companies in 1985 to provide standardized physical productivity measurements. The model plant has been used for other studies including two benchmark productivity analyses, an analysis of multifunctional equipment, and an economic analysis of multiskilled workforce. The project consists of a petro-chemical processing facility to be built in Baytown, Tex. The project was estimated to cost \$85 million (Burleson et al. 1998). The current value of the model plant is \$140 million (Pappas 2004).

With the help of project managers of petro-chemical processing facilities and several scheduling experts, Burleson et al. (1998) developed a schedule for the model plant. The project schedule extends over 77 weeks based on a working schedule of four 10 h days/week. For the purpose of this study, the complete labor demand profile of 77 weeks was selected for the illustration of the optimization model.

As previously explained, in order to meet job site demands the model might call for training some workers in more than one skill. The output of the model includes the number of workers to be trained in more than one skill and the specific skills in which workers should be trained. Training a construction worker to be fully skilled in an additional craft requires a significant investment from the employer. Based on interviews with industry professionals using in-house instructors and National Center for Construction Education and Research (NCCER) materials, Pappas (2004) estimated a cost of \$2,000–\$5,000 to upgrade a worker from 1.5 to 2 certified crafts. Therefore, the cost of training a worker to be fully skilled in an additional craft is expected to fall in the \$4,000–\$10,000 range.

This study, however, does not call for training workers to be fully skilled in an additional craft. Rather, it calls for training workers in additional crafts in order to effectively contribute to the work without having to possess mastery level skills in the additional craft. Furthermore, the cross training of the workers is not necessarily performed in a formal fashion. Training can be performed through an on-the-job mechanism where the worker with the most expertise in a certain craft can assume the role of the mentor and the remaining members of the crew can assume the role of apprentices or helpers. Either way, it is reasonable to assume this training can take place before or during the project with enough lead time before actual need. For the purpose of this study, the "basic" cost of training a worker to be proficient in an additional craft is assumed to be \$2,000. This figure will be increased depending on the affinity coefficient between the worker's original craft and his/her additional craft. The following equation illustrates the simple calculation of the cost to train in skill j a worker who already possesses skill i (trainingcost_{ij}) as the basic training cost (traincost_{ij}) divided by the corresponding affinity coefficient

$$\text{trainingcost}_{ij} = \frac{\text{traincost}_{ij}}{\alpha_{ij}}$$

As explained by Pappas (2004): "some combinations of skills or crafts are naturally more desirable or useful than others." Based on the same CCIS/CII survey, a bivariate correlation analysis was performed across all considered crafts. Srour (2005) pre-

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Table 1. Case Study 1—Hiring and Training Recommendations

Hiring Recommendations					Training recommendations		
Single-skilled workers		Multiskilled workers			Primary Skill	Skill to be trained in	
Welder	12	Welder	Carpenter	1	General labor	Rigger	1
Carpenter	7	Carpenter	Welder	1			
Painter	6	Carpenter	Painter	1			
Ironworker	5	Carpenter	Ironworker	1			
Equipment operator	4	Carpenter	Concrete finisher	2			
Crane operator	1	Ironworker	Welder	1			
		Ironworker	Rigger	1			
		Equipment operator	Instrumentation	2			
		Equipment operator	Crane operator	2			
		Concrete finisher	Carpenter	1			
		Crane operator	Equipment operator	2			
		Rigger	Ironworker	1			

sents in detail correlation figures as well as other model input data. The idea is to test which pairs of skills are most likely to be combined. For example, ironwork and welding are more likely to be combined than instrumentation and pipefitting. Positive correlation values generally indicate an "affinity" between the two considered skills, whereas negative values indicate that the two skills are not likely to be combined in practice. The bivariate correlation values were changed to provide coefficients between 0 and 1, with higher values indicating crafts that are likely to be combined in practice.

The hiring costs figures that are used in this study were determined based on the proposed economic model of Burleson et al. (1998). They are composed of the following terms:

1. Recruiting and screening costs: estimated at $500/worker. This figure includes application, interview, reference checks, and other tests;
2. Employee orientation costs: these include the cost of materials such as handbooks, company packets, and badges that are provided during the orientation session. An 8-h orientation session was determined for the model plant project. This study assumes an employee orientation cost of $150/worker;
3. Worker qualification costs: these include both owner initiated requirements and state or local regulatory requirements. For example, all individuals working at a project site in the Houston area petro-chemical construction sector must have completed the Houston Safety Council training and examination. This study assumes an incurred safety Council training cost of $50/worker for all workers. It also assumes that all hired welders will need certification, which costs $150/worker; and
4. Small tools and personal protective equipment costs: Personal protective equipment (PPE) includes hardhats, gloves, ear plugs, safety harnesses, and goggles, which are often provided by the contractor. Contractors sometimes also provide small tools for job use. These are often lost, stolen, or damaged and therefore they must be replaced. This study uses $600 for the combined costs of PPE and small tools replacement.

In summary, this study assumes a hiring cost of $1,300/worker for all hired workers except welders who are assumed to have a $1,450 hiring cost/worker.

One of the barriers for implementing multiskilling is the adoption of a wage scale depending on the number of possessed skills. Construction workers can be reluctant to receive training in an additional skill unless it reflects in their pay rates. On the other hand, contractors and owners are often reluctant to make significant changes to their wage rates to reward multiskilled workers. This study assumes that the hourly wage of a worker who possesses skills i and j is the higher of the following two figures: the wage of a worker who possesses skill i only and the wage of a worker who possesses skill j only. The hourly wages of single-skilled workers were obtained from the 2004 Bureau of Labor Statistics data (BLS 2004) and from the CCIS/CII survey—a survey of 982 construction workers at 19 sites across the United States (Brandenburg 2004). The wage rates used in the OWIM were assumed to fall between the figures obtained from the CCIS/CII survey and those obtained from the BLS (Srour 2005).

Finally, hypothetical figures were assumed for the training and hiring capacities in the different considered crafts in this study. These figures, which are presented in Srour (2005), were changed as part of the five case studies that are presented next.

Results from Five Case Studies

The formulated model was applied to five different case studies reflecting different real-world scenarios. While summary results are generally presented in the following analyses, it should be emphasized that each run of the model results in specific hiring and training recommendations.

The first case, Case study 1, assumes the availability of a large pool of workers from which to hire (both single skilled and multiskilled), as well as sufficient training facilities. As shown in Table 1, the model recommends hiring workers rather than training. This is an expected result since the hiring costs are less than the training cost between any pair of crafts. Also, this result reflects the common practice of cross training workers in additional skills only if needed. In the "real-world," the preference is often given to hiring additional workers over cross training the available ones. Another observation is that the model recommends hiring as many multiskilled workers as possible to satisfy job site demands as illustrated by the fact that most of the hiring capacity constraints on multiskilled workers are tight. This is an expected result since multiskilled workers can be assigned to more than one craft at different time periods, which reduces the need to hire single-skilled workers to fill the gaps between labor demand and supply curves.

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Table 2. Comparison of Results from Five Case Studies

Description	Case study 1 Training & hiring available	Case study 2 Can not train	Case study 3 Can not hire multiskilled	Case study 4 Can not hire single-skilled	Case study 5 Can not hire at all
Training cost ($United States)	2,666.67	0	16,000	41,333.33	142,000
Hiring cost ($United States)	68,550	69,850	75,050	40,050	0
Wages incurred ($United States)	8,888,940	8,891,360	8,885,540	8,908,720	8,909,740
Total costs ($United States)	8,960,157	8,961,210	8,976,590	8,990,103	9,051,740

Four additional cases were studied. Case study 2 assumes the same conditions as Case study 1 except that training is not available. Case study 3 assumes the same conditions as Case study 1 except that it is not possible to hire multiskilled workers. Case study 4 assumes the same conditions as Case study 1 except that it is not possible to hire single-skilled workers. Finally, Case study 5 assumes it is not possible to hire any worker (single-skilled or multiskilled) and therefore cross training is the only solution to meet job-site demands. This scenario is likely to happen on projects in remote areas with limited availability of labor. Table 2 summarizes the outcomes of the model runs for the five case studies.

As shown in Table 2, the wages incurred on site represent the highest component in the total labor cost figure. This is due to the size of the project and its relatively long duration (77 weeks). A comparison between Case study 1 and Case study 3 indicates that the imposed limitation on the hiring of multiskilled workers resulted in a reduction of $3,300 in incurred wages, which is expected since the wages of multiskilled workers are higher than the wages of single-skilled workers. Nonetheless, this limitation resulted in an increase in training costs of $13,333 and an increase in hiring costs of $6,500. This result indicates that the benefits of employing multiskilled workers outweigh the associated costs. Finally, a comparison between Case study 1 and Case study 5 indicates that the strict limitation on the hiring of workers results in an increase of $91,583 in the overall labor costs.

Sensitivity Analyses

Fig. 2 presents the variation in the number of workers to train or hire, as recommended by the OWIM, resulting from running the model on Case study 1 while varying the basic training cost per worker (initially set at $2,000 per worker). As expected, training becomes a less attractive option than hiring as the training cost per worker increases. Both options are equally attractive when the training cost is roughly $1,000/worker, which translates into a training cost of $1,000–$4,000/worker after adjusting for skill affinity. When the basic training cost exceeds $3,000/worker, the model does not recommend training any worker; instead, it recommends hiring workers, single skilled and multiskilled. Beyond this point, the solution of the model and the cost figures do not change.

Fig. 3 presents the variation in the number of workers to train or hire as recommended by the OWIM, resulting from running the model on Case study 1 while varying the basic hiring cost per worker, initially set at $1,300. As expected, hiring becomes a less attractive option than training as the hiring cost per worker increases. Both options are equally attractive when the hiring cost is in the vicinity of $2,500/worker. When the hiring cost reaches $7,000/worker, the OWIM does not recommend hiring any worker; instead, it recommends only cross training workers in additional skills. Beyond this point, the solution of the model and the cost figures do not change.

Computing Effort

The execution time to solve any of the case studies presented in this paper is about 1 s. For example, the time spent by the general algebraic modeling system (GAMS) and the CPLEX solver to run case study 1 is 0.909 s.

One of the reasons that explain the relatively short time required to solve the OWIM is the fact that (CPLEX) has a "presolve" option, which has the ability to reduce the size of the formulated problem (Brooke et al. 1998). For the OWIM, this option eliminated 6,288 constraints out of 19,891 and 17,337 decision variables out of 36,271 prior to calling the CPLEX Solver. Another reason behind the short execution time is the fact that only a small number of the constraints are tight. For example, the set of constraints relating the demand for workers with skill i during time period t to the number of workers with skill i available during the same period are tight only for a few weeks out of the 77-week project schedule. This phenomenon happens around the peak of the bell-shaped labor demand curves.

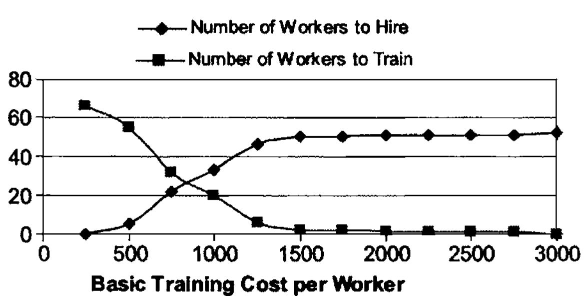

Fig. 2. Typical relationship for number of workers to hire or train versus basic training cost per worker resulting from varying training cost per worker

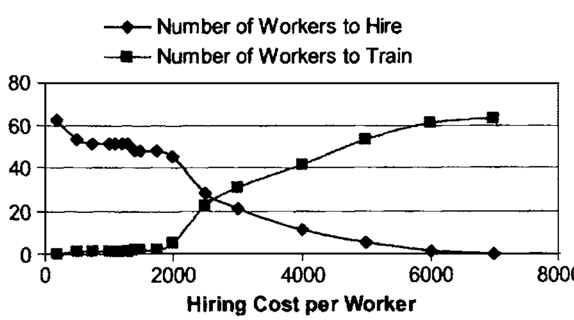

Fig. 3. Typical relationship for number of workers to train or hire versus hiring cost per worker resulting from varying hiring cost per worker

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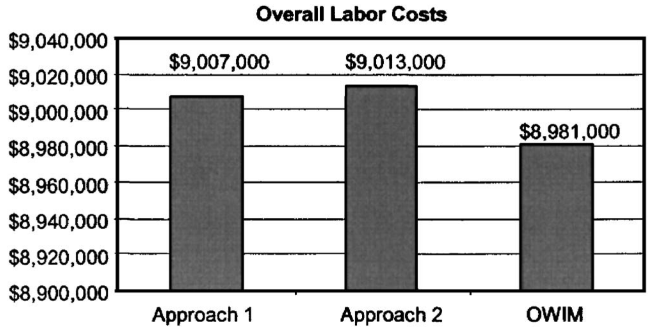

Fig. 4. Comparison of overall labor costs using Approach 1, Approach 2, and OWIM

Estimate of Benefits and Costs of Implementation of OWIM

This section presents an assessment of the benefits and costs associated with implementing the OWIM. Based on the previously made assumptions, a new case study was developed. The results obtained from the application of the OWIM on this new case study are compared to two likely approaches representing what an industry practitioner carry out instead of using the OWIM. Additional nonquantifiable benefits and costs are also presented.

When faced with the problem of shortages in some trades and with surpluses in others, industry practitioners might opt for one of the following two options (without using to the OWIM), named "Approach 1" and "Approach 2" respectively:

1. Approach 1: hire workers to fill the gaps between the labor demand and the labor supply profiles; and
2. Approach 2: cross train workers from the trades facing surpluses in order to allow them to work in the trades facing shortages.

Based on the input data presented earlier (labor demand profile, labor availability, hiring and training costs, skill affinities, and hourly wages), a new case study, entitled Case study 6, was developed to allow for the comparison of the results obtained from the application of the OWIM with the results obtained from Approaches 1 and 2, respectively. Case study 6 assumes the same labor profile, wage figures, hiring costs, and skill affinities that were previously described. The basic training cost was assumed to be $1,000/worker, which implies that the training cost between any pair of skills falls in the $1,000–$4,000 range (after adjusting for the skill affinities between pairs of skills). This assumption was made to present training as an equally favorable option as hiring (hiring costs fall in the $1,300–$1,450 range).

As shown in Fig. 4, the overall savings obtained by using the OWIM instead of Approach 1 are approximately $26,000 (i.e., $9,007,000 − $8,981,000) and the overall savings obtained by using the OWIM instead of Approach 2 are $32,000 (i.e., $9,013,000 − $8,981,000).

The implementation of the OWIM in the real world has some associated cost elements. An easily quantified element is the cost incurred in purchasing the required software package in which the OWIM can be formulated and then solved. A combination of GAMS and CPLEX with the possibility of solving linear programs only can be purchased for $6,000 (GAMS 2004). Therefore, the overall cost to purchase the technology required to implement the OWIM is less than the aforementioned savings in overall labor costs of approximately $30,000 ($26,000 and $32,000 using Approaches 1 and 2, respectively). However, this cost figure of $6,000 does not include the cost of training an employee of the company in operating the required technology, the cost of changing the administrative procedures within the company in order to integrate the OWIM into the current human resources system, and the cost of using the model on a real project.

The job of the operator includes entering the model input data such as labor demands over the considered time period, labor availability, training capacity, and hiring capacity. Also, the operator should have the ability to run the model and present the output to the decision maker in the company. The training of a staff member in using the OWIM is estimated to take 2–3 working days, which yields an approximate cost of $2,000.

The process of altering the administrative procedures within the company in order to integrate the OWIM into the current human resources system entails developing the required databases of workforce profile (single-skilled and multiskilled), skill affinity coefficients, hiring costs, training costs, hourly wages, estimates of worker availability for hiring, and estimates of training capacities. This process is estimated to take 1–2 weeks or approximately $8,000.

The aforementioned cost elements associated with the implementation of the OWIM represent a one-time investment of $16,000 regardless of the number of projects on which the OWIM will be implemented. The last cost element, however, depends on the number of projects on which the OWIM will be implemented. This relates to the process of entering data to the OWIM, running the model, and analyzing the results (training and hiring recommendations and summary costs). This process is estimated to take 4 h/project or $400.

Table 3 presents a summary of a benefit-to-cost analysis for the implementation of the OWIM by a large construction firm. This assumes that the construction company is in the process of planning for its labor strategies across ten projects approximately similar in size to the CII model plant.

Table 3. Summary of Estimate of Costs and Benefits

Benefits	$30,000×10 = $300,000
Technology costs	$6,000
Staff training costs	$2,000
Administrative procedures costs	$8,000
Data input, model running, and analysis of results	$400×10 = $4,000
Benefit-to-cost ratio of implementing the OWIM	$300,000/$20,000 = 15/1

Future Work on OWIM

The formulation of the OWIM assumes that the workers currently employed will be offered a chance to receive basic training in only one additional skill. This assumption was based on previous studies which indicated limited benefits for cross training workers in more than one additional skill (Gomar et al. 2002; Campbell 1999; and Burleson et al. 1998). One of the conclusions of the study of Gomar et al. is that the benefits of extended employment duration are marginal after workers possess skills in two or three crafts. It will still be beneficial to extend the formulation to allow for the option of training in more than one additional skill.

The current formulation of the OWIM can be altered to incor-

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porate elasticities. For example, the task of finding skilled workers becomes harder once a certain number of workers are hired. In this case, the cost of hiring a worker is expected to rise. This phenomenon can be captured in the OWIM by splitting the number of workers to hire decision variable into multiple decision variables with each in a sequence representing the number of workers that can be recruited at increasing hiring costs and/or wages rates. In addition to these new variables, constraints representing the maximum number of workers that can be hired at each set of hiring costs and wage rates are needed.

Adding a skill level dimension to the formulation could also be useful. This can be done by dividing the workers into helpers/apprentices, journeymen, and foremen. The model would offer the option of training a helper with skill i to become a journeyman in the same skill, training a helper with skill i in an additional skill j, or training a journeyman with skill i in becoming a helper in skill j. It is also recommended to change the model formulation in order to allow for training workers in administrative or management skills.

Finally, future studies in this field may benefit from previous work in agent-based modeling, "a methodology in which a simulation experiment is constructed around a set of autonomous agents that interact with each other and their underlying environment to mimic the real-world scenario that the replicate" (Sawhney et al. 2003). A model can be developed at a corporate level or for a certain region such as the Gulf Coast area where there is sufficient construction work for the local labor pool. Hence, workers don't need to leave the region to be employed. The different projects in this region can be viewed as independent agents interacting with a common pool of labor. Long-term demand curves for this area need to be generated. The model can incorporate potential elasticities in supply and demand of labor. The investment in the available labor pool can come from a regional organization such as the Houston Business Roundtable which is interested in improving the skill sets of its labor pool in order to meet job site demands in the most cost-effective fashion. In this context, several questions arise: is there a breakpoint at which all the firms start training? Will the training be provided by contractors, owners, or both? When will the workers themselves recognize the benefits of cross training?

Conclusions

A review of the relevant body of knowledge revealed the need for optimization techniques to address the issue of investment in the construction workforce. These techniques have the potential to help alleviate problems of skilled labor shortages. A linear programming model was developed to provide an optimization-based framework for matching supply and demand of construction labor through training, recruitment, and allocation. The model entitled OWIM serves as a useful tool for planning using commercially-available software. The OWIM was applied on data obtained from the CII model plant and a recent survey conducted by the CCIS and CII.

When compared with possible approaches taken by an industry practitioner faced with the problem of shortages in some trades with surplus in others, the OWIM provided savings of approximately \$30,000 in overall labor costs, as compared to the approximately \$9 million total labor costs. A comparative study of the benefits and costs associated with the implementation of the OWIM by a large construction company in the process of planning for its labor strategies across ten projects of the size of the CII model plant revealed a benefit-to-cost ratio of 15:1. It is important to note here that this value would significantly increase if the model is applied on additional projects. This is due to the fact that most of the cost elements are incurred only once.

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