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ASSIGNMENT AND ALLOCATION OPTIMIZATION OF A PARTIALLY MULTISKILLED WORKFORCE

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Chapter 1

Introduction

1.1 Introductory Statement

Sixty percent of construction companies surveyed by the Business Roundtable in 1997 reported difficulties recruiting and maintaining their workforce (BRT 1997). The poor image of the industry makes it difficult to attract new workers, and the lack of opportunities for training and career growth leads to high turnover rates (BRT 1997; Liska 1998). Several sources indicate that this trend will not soon change. To be competitive in the construction industry, it is necessary to consider other strategies to counterbalance the negative effects of this trend. One potential solution is a workforce strategy called multiskilling.

Research results indicate that multiskilling can increase the productivity, quality and continuity of work, while providing for a safer site and providing managers more flexibility in assigning tasks (Rodriguez 1998). Multiskilling also has been proven to have potential benefits for the workforce. They include longer employment duration, better qualifications resulting in increased employability, and increased job satisfaction (Stanley 1997, Carley 1999).

The success of multiskilling greatly relies on the foreman's ability to assign workers to appropriate tasks and compose crews effectively. The foreman assigns tasks to workers according to their knowledge, capabilities and experience on former projects (Rodriguez 1998). To obtain the maximum benefits from multiskilling, practitioners have stated that automated tools that optimize allocation and assignment of workers would be valuable (Rodriguez 1998). This research describes efforts directed toward developing tools that optimize the allocation and assignment of multiskilled workers to activities in a construction project.

A multiskilled workforce for this research effort is one in which the workers possess a range of skills that allow them to participate in more than one work process. Because craft boundaries are blurred using multiskilling, a multiskilled workforce can be organized in such a way that workers are employed for a maximum time at the site while the total project hiring requirements are reduced. A worker may be selected to participate in any activity in which he or she is proficient and may be rotated to another activity, if necessary, rather than hire an additional worker. Table 1.1 shows an example of three workers that are proficient in more than one skill.

Table 1.1 Example of a pool of multiskilled workers

Name	Equip. Oper.	Concreter	Carpenter	Ironworker
Jose	X		X	
Christine		X	X	X
Kevin	X	X		X

1.2 Objectives

The objectives of this research were to: (1) develop a model to optimize the workforce resource allocation and assignment process of a partially multiskilled workforce, (2) test and evaluate the model using the Construction Industry Institute (CQ) Model Plant Data (Construction Industry Institute 1988), and (3) to use the model and the data to understand the mechanics and trade-offs of multiskilling.

1.3 Methodology

Three primary sources of information are used in this report; the Center for Construction Industry Studies (CCIS) Workforce Research Team, the Construction Industry Institute (CII) Model Plant Data, and published literature. Members of the CCIS Workforce Research Team provided knowledge of current human resource management practices and multiskilled uses in the construction and other industries. The research team was comprised of an Advisory Panel of upper level management from CII member companies, faculty from the University of Texas at Austin, and student researchers. Members of the Advisory Panel represent some of the major contractors and users of construction services in the United States.

A literature review provided documented examples of multiskilling and of labor allocation optimization case studies. However, little detail or background data was available directly from these sources. Previous research provided a general path toward potential improvements through the use of multiskilling. Operations Research and Decision Sciences literature illuminated what are considered to be the current fundamental labor allocation problems and optimization techniques for solving those problems. None of the existing techniques were directly applicable.

The CII Model Plant, provided detailed project information from a hypothetical petrochemical plant, which was designed and analyzed by CII for research purposes. The labor aggregation data from the Model Plant was used to validate the model developed in this research effort. The CII Model Plant will be described in the following sections of this report.

These information sources were used to help develop a model that optimizes the allocation process for a multiskilled workforce. The Multiskilled Allocation Model for Optimization (MAMO) was tested and validated using the CII Model Plant data and commercial linear programming software. The Model Plant was developed by the Construction Industry Institute (CII) member companies in 1985 to provide standardized physical productivity measurements. Since its development, the Model Plant has been used in two benchmark productivity studies, used as a basis for analysis of multi-functional equipment, and as basis for analysis in the development of an economic model for a multiskilled workforce (Burleson 1997). The optimization tests were conducted in the General Algebraic Modeling System (GAMS). GAMS (Brooke, Kendrick and Meeraus, 1992) is especially useful for handling, large, complex, one-of-a-kind problems which may require many revisions to establish an accurate model like the model developed by this research. Finally, the results of the tests were analyzed in order to understand the mechanics of multiskilling.

1.4 Report Structure

The structure of this report follows a conventional format. Chapter 2 includes a brief discussion of other research results and studies conducted on multiskilling and allocation optimization. Chapter 3 describes the model objectives and its capabilities. Chapter 4 analyzes multiskilling characteristics using the model as the testing medium. Chapter 5 presents conclusions and recommendations drawn from this research.

Chapter 2

Background and Literature Review

This chapter presents background information and the results of a literature review. These results form the basis of the model and its objective functions which are described in the following chapter.

2.1 Multiskilling and Economic Benefits

Current construction methods are very labor intensive, and it is not uncommon for labor costs on a project to account for 30%-50% of the total project costs (Adrian 1987). However, even though labor accounts for such a large fraction of the job costs, there have been few changes in labor utilization strategies that improve the effectiveness of labor.

Borcherding (1972) performed research that attempted to determine the factors that influence craft productivity on construction sites. Others have also performed research using worker surveys, foreman delay surveys, work sampling, and other measuring techniques to identify the causes of low productivity (Alfeld 1988; Rogge 1981; Thomas 1990; Thomas 1991). The results of many of these studies have been improvement programs that focus on inefficiencies on the construction site and in the communication process between upper management and the foremen and workers on the site.

Demotivation of workers has been identified as one of the primary reasons construction labor inefficiencies occur. Demotivating factors identified include discontinuity of job assignments and a feeling of purposelessness due to idle time on the job site. Both of these demotivators negatively impact the attitude of the worker and act to lower his or her overall productivity.

Many construction craft workers also face the problem of short employment duration, frequent layoffs, and periods of unemployment between jobs because of the flow of work and manpower fluctuations experienced in the construction industry. According to Maloney (1987) in a 1986 survey of 404 open shop construction workers, the average employment duration for 1983 was only 42.1 weeks and the average number of layoffs per year per worker for the last five years was 2.5. As a result, the net annual income for many construction workers is low. While this problem is less prevalent at the turn of the millenium, it is a recurring one historically.

Multiskilling is a labor technique that addresses many of the above stated problems (Williamson 1992, Cross 1996, Burleson 1997, Stanley 1997, Villalobos 1997, Carley 1999, Rodriguez 1998). With multiskilling, workers may expect to have longer employment durations, continuity of job assignments, and reduced idle time. Potential byproducts of multiskilling are increased efficiency, increased safety, lower personnel costs, and lower total labor costs.

The Business Roundtable (BRT) recognized decades earlier that more flexibility of work assignments across craft lines would produce a more stable workforce through a transfer of people within a construction project (1983). Combining crafts into groups for the purpose of specific tasks would give the contractor the capability to assign the work in a more flexible and efficient manner. Four trade groups were suggested by the BRT: mechanical, electrical, civil, and support.

Previous research by CH has demonstrated that multiskilling has the potential of increasing average employment duration on a job 18% to 47% and decreasing the necessary labor force up to 35% (Burleson 1997). Other results indicated potential labor cost savings ranging from 4.7% without any productivity increase in the labor force due to multiskilling to an 18.9% total cost savings with a 15% productivity increase.

Some believe, that multiskilling improves productivity due to the benefits stated. For example, an average increase of 20% due to multiskilling was estimated by six of the companies that were surveyed in one study (Rodriguez 1998). It is reasonable to be skeptical of these estimates, however. For instance, the companies in this study have not accurately measured increases in productivity, partly because the varied nature of each project makes an exact value difficult to obtain. Also, the shift to a multiskilled workforce strategy has not typically been a perfectly ordered one.

2.2 Scheduling and Implementation of Multiskilling

A previous study focused on documenting current practices for scheduling a multiskilled workforce and, based on these practices, formalizing a method to implement this labor strategy (Rodriguez 1998). A flowchart of the suggested methodology for planning and implementing a multiskilled workforce is included in Appendix A.

The research concluded that multiskilling should be evaluated for each phase of a project in order to take advantage of its benefits, where applicable. It should only be implemented in a project after it becomes a part of the company's managerial scheme, and after training, recruiting, and compensation strategies have been determined. Use of a multiskilled workforce should be planned properly for each project to maximize compensated time, reduce labor requirements, and ensure it includes the skills required by the project.

The research also concluded that the success of multiskilling greatly relies on the foreman's ability to assign workers to appropriate tasks and organize effective crews. The surveyed companies possess a simple database in which the information regarding the skills and experience of workers is contained. However, these databases are rarely consulted as resources to assemble crews, or to move labor between local or regional projects. This process can be improved.

2.3 Workers' Attitudes toward and Experiences with Multiskilling

Another study focused on the workers' attitudes towards and experiences with multiskilling (Carley 1999). This research was conducted by surveying workers in many different areas of the construction industry and conducting statistical analyses of the results.

It was discovered that approximately 70% of the survey's respondents have worked in trades other than their primary trade, and that over 79% of those workers sampled are interested in learning more skills in their primary trade. Approximately 57% were interested in learning another trade. Overall, workers are interested in learning those trades that require high skill levels and that are physically less demanding than other trades. These trades and types of work include instrumentation, welding, and electrical work.

The majority of workers surveyed believe that multiskilling will significantly affect their work. Multiskilling will allow them to enjoy their work more, stay on a project longer, allow for more responsibility, create a more mentally challenging job, receive better pay for their work, provide for more rewarding work, and allow them to work for the same company longer. Workers are willing to learn additional skills if they are compensated for the work by additional pay, benefits, challenging work assignments, and more responsibility.

2.4 Assignment Optimization

Additional literature was reviewed in the areas of construction, operations research, and human resources management. The objective was to gather information on previous work in multiskilling, and allocation and assignment optimization. Most of the literature found was related to other industries.

Multiskilling is currently being used in the facility maintenance and manufacturing industries. Facility maintenance is a primary application. Companies such as National Steel, Motorola, Hoechst Celanese, and Rohm and Haas are using multiskilled labor strategies in some of their plants. Documented benefits include increased productivity, lower personnel costs, lower turnover levels, increased quality, and increased worker satisfaction (Cross 1989; Denton 1992; Carmichael and MacLeod 1993; Alster 1989; Williamson 1994). Other potential cited benefits include smaller crews, shorter equipment downtimes, and increased earnings for employees (Williamson 1992).

Single-skilled workers in manufacturing may constrain new technology from developing by using it inefficiently; multiskilling will help in the introduction of technical change (Carmichael and MacLeod 1993). The resistance to technical change is often partly due to the fear of displacement. Multiskilled workers are skilled at more than one task, so when change occurs they can be transferred to other jobs. Technical change can be advantageous to multiskilled workers as they move from one job to another because it will gradually increase their level of skill. Workers with more than one skill are shown to be open to technical change and volunteer ideas for continuous improvement (Carmichael and McLeod 1993). Multiskilling wages are attached to the worker, while single-skilled wages are reflective of the job that is performed.

Productivity increase is an essential motivator to the use of multiskilling. Multiskilling may be used in some circumstances to reduce work crew size, which requires workers to increase their effort to learn. The increased learning effort derives from smaller crews and constantly changing crews that are sometimes new to the type of jobs being performed. Therefore, the skills and work assignments of a worker in a smaller multiskilled crew must be assumed by one or more workers who now have to perform additional duties in addition to their own work assignments (Cass 1992). This may negatively impact the potential productivity increases normally associated with multiskilling. It suggests that in order for multiskilling to be effective it is desirable to maintain constant crew sizes and minimize switching of workers from one crew to another crew or one activity to another. In general, switching workers between crews and jobs decreases productivity through transaction costs and learning curve effects.

Brusco and Johns (1993) studied the staffing of a multiskilled workforce with varying levels of productivity using the operations of a paper mill facility as a model. The research was conducted using an integer goal-programming model, which was tested by collecting data from the maintenance operations at the paper mill. The breadth and depth of a multiskilled workforce were primary variables in this study: breadth was represented by the number of skill categories for which employees are cross-trained, and depth by how skilled workers are in a particular skill. Different breadths and depths were measured to test the trade-offs between these two factors. This study concluded that the breadth of cross-training had a tremendous effect on the required workforce size and is more important than the depth of cross-training.

Campbell (1999) developed an optimization model for allocating cross-trained workers in a multi-department service environment. Worker capabilities were described by parameters that range from 0 to 1, with fractional values representing workers who are less than fully qualified. The model developed was developed in a series of experiments to investigate the value of cross-utilization as a function of factors such as demand variability, cross-training breadth, and cross-training depth. Results showed that the benefits of cross-utilization can be substantial, and in many cases a small degree of cross-training or breadth can capture most of the benefits. Beyond a certain amount, additional cross-training adds little additional value, and the preferred amount depends heavily on the level of demand variability.

Bechtold (1988) studied a tractable set of integer programming models of a mix of full- and part-time employees in a multiple-objective, multiple-location environment. The first three models developed analyze trade-offs between idle time, the number of employees required to work at multiple "locations", and the size of the total labor pool. The flexibility of this approach is illustrated by a series of modifications made to the constraints that change the objective function and permit the use of preference weights to influence the solutions. Models may be formulated so idle time is ignored, constrained or minimized. This study concluded that minimizing total idle time and number of employees could be simultaneously achieved.

Allocation and scheduling optimization have been ongoing goals in construction research. Recent models have focused on the optimization of the schedule of a project, taking into consideration several factors such as investment allocation, total cost, resource supply, and weather (Li 1995, Hegazy 1999). Genetic Algorithms have been used for approximately optimizing allocation and leveling of resources (Hegazy 1999). This technique is a heuristic search that considers leveling and allocation simultaneously. The technique suggested provides an alternative to the technique used by Primavera Project Planner with its leveling capabilities.

Chapter 3

Assignment and Allocation Model

3.1 Model Objectives

The main objectives of the model developed by this research effort were: (1) to minimize the total number of workers used on a project, (2) to increase their employment duration on the construction job, (3) to minimize hires and fires of workers, and (4) to minimize the number of switches of a worker from crew to crew. These objectives were selected because they reflect the challenges of planning and scheduling in the field, and because achieving them results in benefits to both the workers and the project. Their justification is further developed in the following paragraphs, and is based on the research presented in the preceding chapter.

The Business Roundtable (BRT 1997) study cited earlier found that nearly nine out of ten chemical and petrochemical companies have experienced difficulty in attracting skilled craft workers to their projects. One of every four companies encountered labor shortages that resulted in serious project impacts in terms of cost overruns and/or schedule delays. *Minimizing the total number of workers* used in a project is one objective of the model developed, because of these shortages.

Recent projections indicate that the construction industry must recruit 200,000 - 250,000 new craft workers per year to meet future needs (BRT 1997). Both demographics and image are working against the construction industry in addressing this need. In addition, construction work is seasonal and has a very high turn-over rate. The multiskilling technique or approach addresses these shortcomings by *increasing the employment duration* of workers due to their versatility. This provides them with higher annual income and an incentive to enter the industry (Carley 1999).

Turn-over on a construction site is a consequence of the shifts in skill requirements over the project duration. Multiskilling reduces turnover by providing a workforce with broader skill sets. Turnover creates costs. The economic model suggested by Burleson (1997) calculates total project labor costs of any type of labor force. This model contains nine factors that include project wages, insurance costs, training and recruitment costs, and others. Hires form part of six out of the nine terms forcing the overall cost of labor to increase whenever new hires increase. Turnover also creates learning costs. Thus it is clear that it is economically advantageous to *minimize the number of hires and thus fires* in the allocation and scheduling process.

"Switching" is the transition of a worker from one working crew to another or from one activity to another. Consequences of switching include disruption of an established production work flow/sequence, imposition of learning requirements for new crews, reduced overall crew efficiency and productivity, and diminished progress accomplished for a given report period (Cass 1992). To lessen these consequences, it is very important to *minimize the shifting of workers from crew to crew* to a point where multiskilling capabilities of workers is beneficial and not disadvantageous.

3.2 Model Capabilities

The mathematical formulation of the multiskilled allocation model for optimization (MAMO) is included in Appendix B, while the formulation as it was programmed in general algebraic modeling system (GAMS) is included in Appendix C. A complete description and exploration of the formulation of the model is beyond the scope of this report, however, it can be found in Gomar (1999). The MAMO model is capable of optimizing the labor allocation and assignment process of a partially multiskilled workforce and a single-skilled workforce. The model suggests what type and how many workers to hire over time, when to switch the workers to another type of job, and when to lay them off completely. The model balances hires and fires with switching, and attempts to yield an optimal solution so as to minimize the amount of workers hired and total cost.

The objective function of the model uses three terms: minimizing total number of workers, minimizing switching (P), and minimizing hires and fires (F).

$$Minimize \quad TOTAL = \sum_{i\in I}\sum_{t\in T} W_{it} + P * \sum_{i\in I}\sum_{j\in J_i}\sum_{t\in T}(Yp_{ijt} + Yn_{ijt}) + F * \sum_{i\in I}\sum_{t\in T} Z_{it}$$

The penalty factors, P and F, are assigned scalar values that affect the last two terms. The P term is the one associated with switching, while the F term is the one associated with hires and fires. It was found through this research that hires and fires directly control idle time.

This model cannot simulate the many human characteristics and the human touch of day-to-day interactions on a construction site. It only suggests a plan to assign workers based on physically tangible objectives; it should be used as a tool to aid planning and not as a replacement of planners.

This model separates workers' allocation (hired) and workers' assignment (Figure 3.1). This histogram represents the allocation process in the "hired" bars, and the assignment process in the "assigned" bars. The demand histogram is derived from a demand schedule which lists the number of each type of skilled worker required on each day. This can be derived from a standard resource loaded CPM schedule or a short interval planning schedule. The demand bars in the example indicate that there is an increasing total demand of workers up to day 4 and then a decrease in demand in day 5, and another increase in demand in day 7.

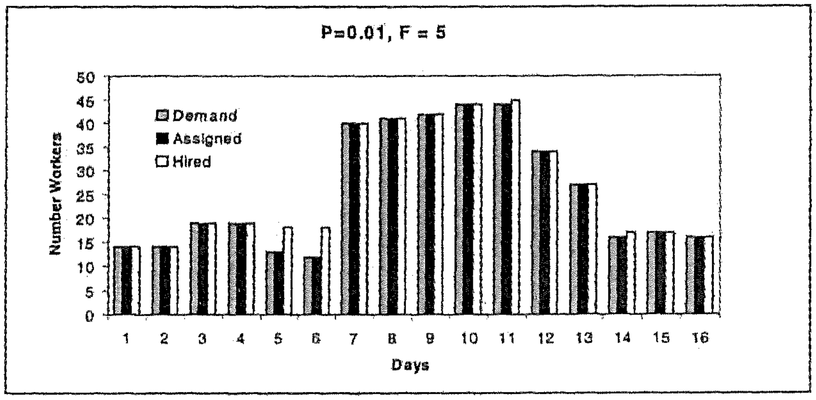


Figure 3.1 Example of a resource histogram of hired and assigned workers.

This could cause workers to be hired and then fired and then re-hired. In practice however, managers assess whether keeping workers on the job during demand gaps is more beneficial than laying them off. They handle these trade-offs intuitively. The model attempts to emulate this economic decision process by capturing the economics into a penalty function that forces the model to make the right decision in conserving workers or laying them off.

It can be observed from Figure 3.1 that the model matches the demands of the project by assigning workers when and where they are needed. The number of workers actually hired or allocated in this example is greater than the number of workers that are needed in days 5, 6, and 14. This may result in some idle workers on the project. (In practice, creative short interval scheduling or scheduled overtime could smooth the demand curve.) Ultimately, the model implicitly decides that it is economically desirable to keep workers on the project in some instances rather than to lay them off and hire other workers with similar skills later. This decision is controlled by manipulating a penalty value (F) that controls the cost of hiring and firing in the model. The lower this value is, the more fires and re-hires will occur, while a higher value will result in a smoother hiring histogram.

The model emulates a superintendent who is trying to decide where all of the workers should be assigned. It selects an optimal set of workers from the pool in order to meet the objectives encoded in the model. In doing so, it may examine an astronomical number of combinations. Although a human brain is very powerful, it is limited when dealing with such complex multi-variable problems. The number of possible work assignments using a multiskilled workforce increases significantly when workers are skilled in several trades. The model is able to tackle the different possibilities in a systematic manner and find the most practical solution. A sample cross-section of the model output related to the example presented in Figure 3.1 is presented in Table 3.1. It illustrates the assignment of workers to different jobs, switching from job to job, idle time, and hires & fires.

Table 3.1 Output of Workers Assignments and Allocations from GAMS.

Worker I.D./Type	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	DAY8
WORKER41.A	1	1	1					
WORKER41.C				1	1	1	1	1
WORKER42.B								
WORKER42.D							1	1
WORKER43.B	1	1	1	1	1	1	1	1
WORKER43.C								
WORKER44.A	1	1	1	1	1			
WORKER44.C						1	1	1
WORKER45.C			1	1				
WORKER45.D							1	1
WORKER46.B	1	1	1	1		1	1	1
WORKER46.C								
WORKER47.A	1	1						
WORKER47.D			1	1			1	1
WORKER48.A	1	1	1	1	1	1	1	1
WORKER48.C								
WORKER48.D								
WORKER49.A			1	1	1	1	1	1
WORKER49.B								
WORKER50.B	1							
WORKER50.C		1	1	1				
WORKER50.D							1	1
Total Assigned	7	7	9	9	5	6	10	10

WORKER41	1	1	1	1	1	1	1	1
WORKER42							1	1
WORKER43	1	1	1	1	1	1	1	1
WORKER44	1	1	1	1	1	1	1	1
WORKER45			1	1	1	1	1	1
WORKER46	1	1	1	1	1	1	1	1
WORKER47	1	1	1	1	1	1	1	1
WORKER48	1	1	1	1	1	1	1	1
WORKER49			1	1	1	1	1	1
WORKER50	1	1	1	1	1	1	1	1
Total Hired	7	7	9	9	9	9	10	10

In Table 3.1, the upper sub-table identifies all worker assignments, and the lower one identifies whether or not a worker is hired, kept, or fired. The upper sub-table identifies the skills that a particular worker will use in a project. For example, W0RKER41 will use skills A and C for the job on activities requiring A and C skills, thus the left most column shows a W0RKER41.A and a W0RKER41.C. W0RKER41 will use skill A from day 1 up to day 3, and will switch to skill C from day 4 to day 8. The bold box at the bottom of the upper table illustrates idle time. Idle time will occur when a worker has been hired but is not assigned to a job. WORKER50 is not assigned to do any job during day 5 and day 6, but if we look at the lower table we can see that WORKER50 is hired and available. Idle time for this model means that a worker is not needed in any of the scheduled work assignments.

Chapter 4
Analysis of Multiskilling

The MAMO model was run repeatedly under ranges of penalty values and workforce pool configurations. The CII Model Plant data obtained from Primavera Project Planner was used to evaluate and validate the model, and although this project was not optimized completely, parts of it were used for the evaluations. The CII Model Plant Data provided all of the demand data, while the supply data, the partially multiskilled workforce, was systematically varied to test the capabilities of the model. Over two hundred tests were conducted using the GAMS software as the testing platform (Table 4.1). Appendix D has a more complete description of the variety of tests conducted. The tests were conducted by varying the percentage of multiskilled workers utilized from 0% of multiskilled workers to 60% of the total workforce. The penalty or control factors of the model, P for switching, and F for hires and fires, were varied systematically to determine their relationship and their influence on the results with respect to the model objectives.

Table 4.1 Model Testing Distribution

Percentage of Multiskilled Workforce	Total Number of Tests
0% (Single-Skilled Workforce)	15
5%	40
10%	40
25%	40
40%	40
60%	40
Total	215

4.1 Diminishing Benefits from Multiskilled Workers

Previous research efforts have determined that when breadth or percentage of multiskilling is increased beyond a certain point, the benefits become marginal (Campbell 1999). The same conclusion was drawn from this research effort. As the percentage of multiskilled workers was increased, the benefits of multiskilling did not increase. The parameter used to measure the benefits was the ratio of total workers hired to the peak workforce needed in a project. The best possible total to peak ratio is 1:1, while the construction industry has an average ratio of 2.7:1 ratio using a single-skilled workforce (Burleson 1997). The tests conducted on the Model Plant data were able to achieve a 2.3 to 1 average total to peak ratio for a single-skilled workforce. This ratio improved significantly with the addition of a multiskilled workforce, but the improvement of this ratio diminished as the percentage of the multiskilled workforce was incremented (Figure 4.1). For each increment of multiskilled workers, several tests were run with values for hires and fires penalty (F) ranging from 1 to 5, and with values of the switching penalty

(P) ranging from 0.01 to 5. These ranges were used because it was observed in initial trial tests that these were the ranges that had the most significant effects on the allocation and assignment results. These values can be calibrated to reflect real costs by aligning model produced plans with those from past projects. The curve in the figure represents the average of the results.

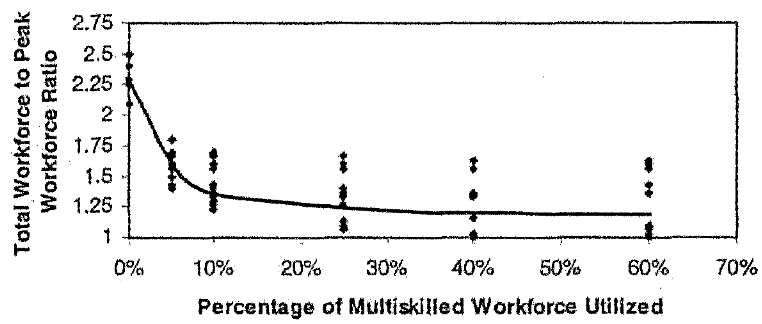


Figure 4.1 Diminishing Benefits from Multiskilling

4.2 Selection of Multiskilled Workers vs. Single-Skilled Workers

Multiskilled workers were consistently selected first during the initial days of the project using GAMS, while the single-skilled workers were always the second choice. This result is consistent with current multiskilling practices in the construction industry where the multiskilled workforce is used as the base for the project as well as in the mobilization phase, and the single-skilled workers are added as needed. Table 4.2 indicates the selection preferences of MAMO for selecting workers at different percentages of multiskilled workforces. The table represents average results for workforce combinations including including 10%, 25%, 40%, and 60% multiskilled workers. As expected, when the percentage of available multiskilled workers increases, the single-skilled workers were selected less often.

Table 4.2 Average Selection Preference by MAMO Between Single-Skilled Workers (SS) and Multiskilled Workers (MS) with Different Percentages of Multiskilled Workforce (%MS).

% MS	Selection Preference	
Workforce	SS	MS
10%	72%	100%
25%	54%	100%
40%	37%	100%
60%	33%	87%

An important result from the model runs is that increased breadth gives the multiskilled workers job security by increasing their job duration. Figure 4.2 shows how the number of skills that a worker possesses increased the participation of that worker on the project. After two or three skills are obtained the extra benefit is marginal. This result also verifies the efficiency of the model in assigning workers, because it is able to obtain optimal solutions without the necessity of utilizing the full breadth of skills of workers with many skills.

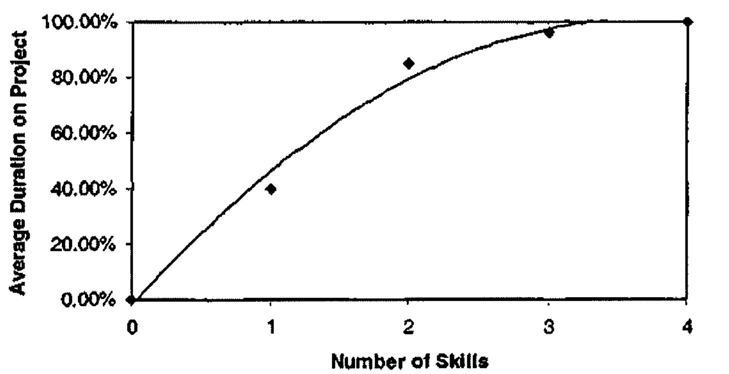


Figure 4.2 Average Duration of Workers on a Project with Respect to the Number of Skills Possessed.

4.3 Turnover and Idle Time

In runs of the model, an expected relationship between turnover (hires and fires) and idle time was demonstrated. This both validates and helps explain the model.

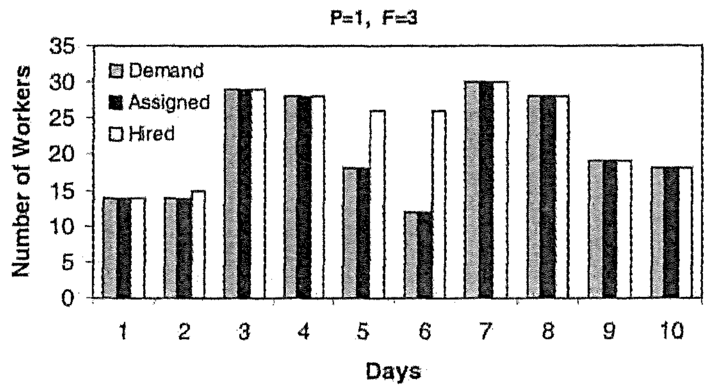


Figure 4.3 Resource Histogram Results after Assignment Optimization of a Segment of the CII Model Plant with a 10% Multiskilled Workforce.

Idle time is the difference between the "Hired" and the "Demand" bars in a resource histogram like the example in Figure 4.3. It can be seen from the figure that the majority of workers for this example were maintained on the payroll for the fifth and sixth day even though the demand decreased. If the hired bars had also decreased by firing workers on those two days and then hiring more workers on the seventh day to meet the demand curve, idle time (the difference of the "Hired" and "Demand" bars) would have been reduced. Idle time decreases as the number of hires and fires increase, and increases as hires and fires decrease. With more hires and fires a planner has the flexibility to meet the demand curves perfectly, however this ignores the turnover costs described earlier. These extra costs are included in the objective function of the model by using factor F.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

Several conclusions can be made based on this research:

1. The assignment and allocation of a partially multiskilled workforce can be optimized with the model presented.
2. Multiskilled workers were always preferred by the optimization model over single-skilled workers.
3. Multiskilled workers should be selected first and used as the base workforce for the duration of the project to obtain better results.
4. The benefits of multiskilling after a 10% to 20% partially multiskilled workforce are marginal.
5. The benefits of increased participation and job duration for workers is marginal after they possess 2 or 3 skills.

To qualify these results, it must be pointed out that in a completely full employment situation where no pool of unassigned or unemployed workers exists, this model has little value. Still it could be used to set strategic targets for skill combinations and their demand volumes for classes of projects.

5.2 Recommendations

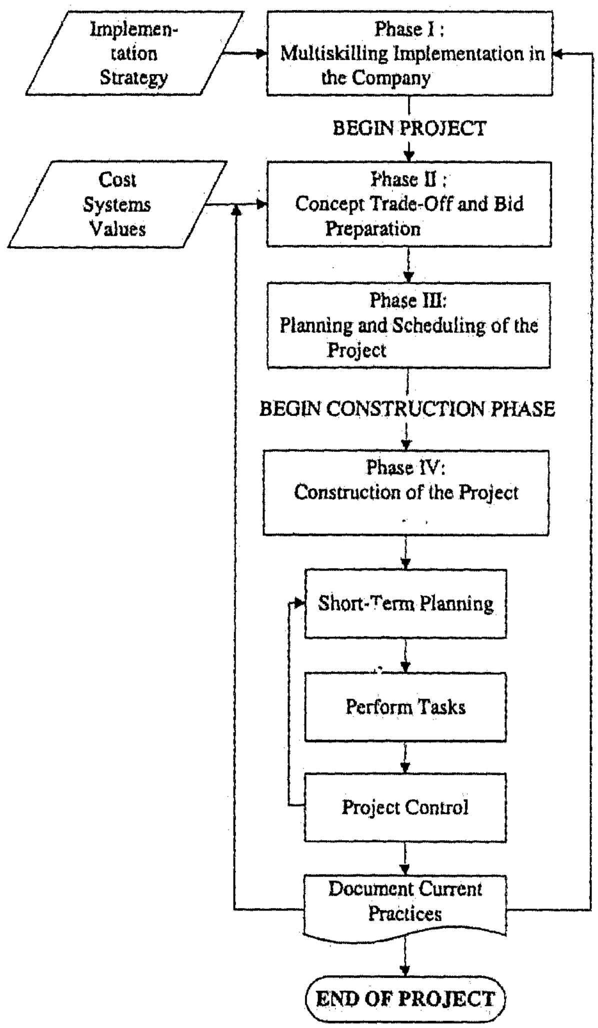
The following recommendations can be made for future research:

1. The results of this research should be tested on various projects and compared to actual construction projects, to determine the benefits that could be gained by using the MAMO model. This should lead to some sense of the value of the model.

2. Models should be further developed to enhance the tools available to the construction industry for assignment and allocation of partially multiskilled workforces.
3. The results of this research should be assessed in conjunction with the human relations perspective.
4. Researchers should expand the model to incorporate two or three basic skill levels in each area.
5. Tests should be run with different skill combinations that represent natural affinities, in order to evaluate the most effective combinations.
6. Values for the penalty factors need to be developed that model the true penalty costs in practice.
7. Multiskilling percentage levels in the 0% to 10% range need to be examined.

APPENDIX A

Flowchart for Planning and Implementing a Multiskilled Workforce



APPENDIX B

Mathematical Formulation of MOMA

Sets:

I set of workers

J set of jobs

T time periods

I_j subset of workers that can do job j

J_i subset of jobs that worker i can do

Data:

$SUPPLY_{ij}$ person i can do job j

$DEMAND_{jt}$ demand of skill j on day t

Decision Variables:

W_{it} worker i hired or allocated on day t

X_{ijt} worker i assigned to do skill j on day t

Yp_{ijt} positive counter variable that measures switching of worker i using skill j on day t

Yn_{ijt} absolute value of negative counter variable that measures switching of worker i using skill j on day t

Z_{it} hires counter variable of worker i on day t

$$Minimize \quad TOTAL = \sum_{i \in I} \sum_{t \in T} W_{it} + P * \sum_{i \in I} \sum_{j \in J_i} \sum_{t \in T} (Yp_{ijt} + Yn_{ijt}) + F * \sum_{i \in I} \sum_{t \in T} Z_{it}$$

s.t.

$$\sum_{i \in I_j} X_{ijt} = DEMAND_{jt} \ldots\ldots\ldots\ldots \quad \forall j \in J, t \in T$$

$$\sum_{j \in J_i} X_{ijt} \leq 1 \ldots\ldots\ldots\ldots \quad \forall i \in I, t \in T$$

$$X_{ijt} \leq W_{it} \ldots\ldots\ldots\ldots \quad \forall i \in I, j \in Ji, t \in T_i$$

$$Yp_{ijt} - Yn_{ijt} = X_{ijt} - X_{ij(t-1)} \ldots\ldots\ldots\ldots \quad \forall i \in I, j \in J_i, t \in T, t \neq 1$$

$$Z_{it} \geq W_{it} - W_{i(t-1)} \ldots\ldots\ldots\ldots \quad \forall i \in I, j \in J_i, t \in T, t \neq 1$$

where $W_{it}, X_{ijt}, Yp_{ijt}, Yn_{ijt}, Z_{it} \in \{0,1\}$ $\forall$ $i \in I, j \in Ji, t \in T$

APPENDIX C

Optimization Model Formulation in GAMS

```
SETS
      I workers /WORKER1 *WORKER10/
      J skills /A, B, C, D/
      Tdays   /DAY1*DAY6/;

 TABLE DEMAND(J,T) demand of skill j on day t

    DAY1  DAY2  DAY3  DAY4  DAY5  DAY6
A    5     5     5     4     5     3
B    6     5     7     5     3     4
C    2     2     4     6     2     3
D    1     2     3     4     3     2     ;

parameter perday(t);
perday(t)=sum(j ,demand(j,t));
scalar biggest;
biggest=sum(t,perday(t));
display biggest;

 TABLE SUPPLY (I,J) supply of worker i that has skill j

                  A   B   C   D
      WORKER1     1   0   0   1
      WORKER2     1   0   1   1
      WORKER3     1   1   1   0
      WORKER4     1   0   1   0
      WORKER5     1   1   0   1
      WORKER6     1   0   1   1
      WORKER7     0   1   1   0
      WORKER8     1   1   0   1
      WORKER9     0   1   1   0
      WORKER10    1   1   0   1;

 SCALAR P penalty factor /.01/;
 SCALAR F rehire factor /5/;
 VARIABLES

      X(I,J,T) worker i with skill j is used on day t (yes or no)
      W(I,T)       hire worker i on day t (yes or no)
      Yp(IJ,T) worker i does same job j as t-1 (positive)
      Yn(I,J,T) worker i does same job j as t-1 (negative)
      Z(I,T)       difference between wit and wit-1 to ensure workers are not hired twice
```

```
TOTAL        total number of workers hired ;

BINARY VARIABLE X;
BINARY VARIABLE W;
POSITIVE VARIABLE Yp;
POSITIVE VARIABLE Yn;
POSITIVE VARIABLE Z;

EQUATIONS

  OBJ                  defines the objective function - minimize total labor
  DEMANDCON(J,T)       meet demand of skill j on day t
  ONEPERDAY(I,T)       worker i can only do one type of job or skill j on day t
  HIREDWORK(I,J,T)     only make assignments to hired workers
  SWITCHING(I,J,T)     limits and measures switching
  HFH(I,T)             ensures workers are not hired fired and hired ;

    OBJ.. TOTAL =E= SUM((I,T), (1.0 + (1.0/(10+ord(i))))*W(I,T)) + P*SUM((I,J,T),
Yp(I,J,T)+Yn(I,J,T)) + F*SUM((I,T), Z(I,T));

    DEMANDCON(J,T).. SUM(I$SUPPLY(I,J), X(I,J,T)) =E= DEMAND(J,T);

    ONEPERDAY(I,T).. SUM(J$SUPPLY(I,J), X(I,J,T)) =L= 1;

    HIREDWORK(I,J,T)$SUPPLY(I,J).. X(I,J,T) =L= W(I,T);

    SWITCHING(I,J,T)$SUPPLY(I,J).. Yp(I,J,T)-Yn(I,J,T) =E= X(I,J,T)-X(I,J,T-1);

    HFH(I,T).. Z(I,T) =G= W(I,T)-W(I,T-1);

MODEL MULTI1 /ALL/ ;

multi1.workspace = 100;

total.lo=biggest;

w.prior(i,t) = 1;
x.prior(i,j,t)$supply(i,j)    = 2;

SOLVE MULTI1 USING MIP MINIMIZING TOTAL;
```

APPENDIX D

Summary of Data tested in GAMS

Table D.1 10% Partially Multiskilled Workforce with varying levels of P&F.

MW .	P	F	Hires	Switches	Time (Min)	Total/Peak
10%	5	1	51	64	0.45	1.7
10%	5	2	42	64	0.31	1.4
10%	5	3	39	64	0.35	1.3
10%	5	4	38	64	0.32	1.3
10%	5	5	39	64	0.37	1.3
10%	1	1	50	64	0.5	1.7
10%	1	2	40	64	0.47	1.3
10%	1	3	38	64	0.47	1.3
10%	1	4	38	65	0.5	1.3
10%	1	5	38	64	0.4	1.3
10%	0.5	1	50	66	0.5	1.7
10%	0.5	2	42	64	0.53	1.4
10%	0.5	3	38	64	0.47	1.3
10%	0.5	4	39	65	0.38	1.3
10%	0.5	5	37	65		1.2
10%	0.1	1	47	68	0.62	1.6
10%	0.1	2	40	67	0.57	1.3
10%	0.1	3	40	66	0.33	1.3
10%	0.1	4	38	66		1.3
10%	0.1	5	37	65	0.3	1.2
10%	0.05	1	47	69	0.67	1.6
10%	0.05	2	41	66	0.52	1.4
10%	0.05	3	39	65	0.4	1.3
10%	0.05	4	37	67	0.4	1.2
10%	0.05	5	38	67	0.35	1.3
10%	0.01	1	48	74	0.66	1.6
10%	0.01	2	43	67	0.48	1.4
10%	0.01	3	37	66	0.4	1.2
10%	0.01	4	37	66	0.38	1.2
10%	0.01	5	37	65	0.32	1.2

Table D.2 25% Partially Multiskilled Workforce with varying levels of P&F.

MW	P	F	Hires	Switches.	Time (Min)	Total/Peak
25%	5	1	50	64	0.95	1.7
25%	5	2	42	64	0.77	1.4
25%	5	3	38	64	0.77	1.3
25%	5	4	34	64	0.66	1.1
25%	5	5	34	64	0.66	1.1
25%	1	1	47	64	31.66	1.6
25%	1	2	40	64	19	1.3
25%	1	3	33	64	13.77	1.1
25%	1	4	33	64	2.33	1.1
25%	1	5	32	64	1	1.1
25%	0.5	1	47	66	25	1.6
25%	0.5	2	40	65	18.5	1.3
25%	0.5	3	33	67	14.67	1.1
25%	0.5	4	33	66	15.01	1.1
25%	0.5	5	32	65	1.66	1.1
25%	0.1	1	47	64	29.66	1.6
25%	0.1	2	41	65	21	1.4
25%	0.1	3	32	68	17.33	1.1
25%	0.1	4	32	66	16	1.1
25%	0.1	5	32	65	2.78	1.1
25%	0.05	1	47	70		1.6
25%	0.05	2	40	65	24.16	1.3
25%	0.05	3	33	65		1.1
25%	0.05	4	32	67	17.16	1.1
25%	0.05	5	32	68	3.16	1.1
25%	0.01	1	48	69	25.66	1.6
25%	0.01	2	41	69	24.88	1.4
25%	0.01	3	33	74	16.5	1.1
25%	0.01	4	32	71	17.23	1.1
25%	0.01	5	32	73	4.5	1.1

Table D.3 40% Partially Multiskilled Workforce with varying levels of P&F.

MW	P	F	Hires	Switches	Time (Min)	Total/Peak
40%	5	1	49	64	30.16	1.6
40%	5	2	41	64	26.5	1.4
40%	5	3	35	64	23.16	1.2
40%	5	4	31	64	4.33	1.0
40%	5	5	30	64	2.66	1.0
40%	1	1	47	64	28.33	1.6
40%	1	2	41	64	31.66	1.4
40%	1	3	31	64	20	1.0
40%	1	4	31	64	17	1.0
40%	1	5	30	65		1.0
40%	0.5	1	47	64		1.6
40%	0.5	2	40	64	25.66	1.3
40%	0.5	3	31	64	21	1.0
40%	0.5	4	30	64	18.77	1.0
40%	0.5	5	31	65	19.77	1.0
40%	0.1	1	47	65	31.8	1.6
40%	0.1	2	41	64	30.16	1.4
40%	0.1	3	31	65	23.66	1.0
40%	0.1	4	30	65	15.16	1.0
40%	0.1	5	30	66		1.0
40%	0.05	1	47	68	26.33	1.6
40%	0.05	2	41	65	22	1.4
40%	0.05	3	31	65	25.16	1.0
40%	0.05	4	30	67	15.33	1.0
40%	0.05	5	30	66		1.0
40%	0.01	1	47	74	17.66	1.6
40%	0.01	2	41	69	18.5	1.4
40%	0.01	3	31	72	23.66	1.0
40%	0.01	4	31	74	17.5	1.0
40%	0.01	5	31	74	16.16	1.0

Table D.4 60% Partially Multiskilled Workforce with varying levels of P&F.

MW	P .	F	Hires	Switches	Time (Min)	Total/Peak	Idle Time
60%	5	1	49	64	29	1.6	0
60%	5	2	43	64	30	1.4	6
60%	5	3	32	64	45.16	1.1	26
60%	5	4	32	64	30.16	1.1	27
60%	5	5	31	64	26.66	1.0	30
60%	1	1	49	64	33	1.6	0
60%	1	2	41	65	20	1.4	7
60%	1	3	33	65	20	1.1	23
60%	1	4	31	65	17	1.0	27
60%	1	5	30	66	20	1.0	30
60%	0.5	1	48	68	40.16	1.6	0
60%	0.5	2	41	66	28.5	1.4	6
60%	0.5	3	31	65	32.33	1.0	27
60%	0.5	4	30	66	15.25	1.0	29
60%	0.5	5	30	67	19	1.0	29
60%	0.1	1	47	66	37.5	1.6	0
60%	0.1	2	41	68	27	1.4	6
60%	0.1	3	31	69	24.16	1.0	26
60%	0.1	4	31	67	35.5	1.0	26
60%	0.1	5	30	67	23.5	1.0	29
60%	0.05	1	47	68		1.6	0
60%	0.05	2	41	67		1.4	6
60%	0.05	3	31	69		1.0	26
60%	0.05	4	30	68		1.0	29
60%	0.05	5	30	68		1.0	29
60%	0.01	1	47	73		1.6	0
60%	0.01	2	41	74		1.4	6
60%	0.01	3	31	81		1.0	26
60%	0.01	4	30	73		1.0	29
60%	0.01	5				0.0	

Table D.5 0% and 5% Partially Multiskilled Workforce total to peak workforce ratios.

MW	Total/Peak
0%	2.3
0%	2.4
0%	2.5
0%	2.1
0%	2.3
0%	2.4
0%	2.4
0%	2.3
0%	2.3
0%	2.3

MW	P	F	Total/Peak
5%	5	1	1.7
5%	5	2	1.4
5%	5	3	1.8
5%	5	4	1.7
5%	5	5	1.6
5%	1	1	1.7
5%	1	2	1.6
5%	1	3	1.6
5%	1	4	1.6
5%	1	5	1.5
5%	0. 5	1	1.7
5%	0.5	2	1.8
5%	0.5	3	1.7
5%	0.5	4	1.5
5%	0.5	5	1.4
5%	0.1	1	1.6
5%	0.1	2	1.5
5%	0.1	3	1.8
5%	0.1	4	1.7
5%	0.1	5	1.7
5%	0.05	1	1.7
5%	0.05	2	1.7
5%	0.05	3	1.5
5%	0.05	4	1.5
5%	0.05	5	1.5
5%	0.01	1	1.4
5%	0.01	2	1.4
5%	0.01	3	1.4
5%	0.01	4	1.7
5%	0.01	5	1.8

APPENDIX E

References

Adrian, James J. *Construction Productivity Improvement,* Elsevier, New York, 1987.

Alfeld, Louis E., *Construction Productivity: On-Site Measurement and Management,* McGraw-Hill, New York, 1988.

Alster, Norm. *What Flexible Workers Can Do,* Fortune, v.199 n.4 pp. 62-66, February 13,1989.

Bechtold, Stephen E., *Implicit Optimal and Heuristic Labor Staffing in a Multiobjective, Multilocation Environment,* Decision Sciences, Vol. 19, No. 2,1988.

Borcherding, John D., *An Exploratory Study of Attitudes that Affect Human Resources in Building and Industrial Construction,* dissertation, Stanford University, June, 1972.

Brooke, Anthony, Kendrick, David and Meeraus, Alex. GAMS. A User's Guide, Release 2.25. The Scientific Press. South San Francisco, California. 1992.

Brusco, M. and Johns, T. *Staffing a Multi-skilled workforce with varying levels of productivity: An analysis of cross-training policies.* Proc, 27th Annual Meeting of the Decision Sciences Institute, Orlando, FL., 1996.

Burleson, Rebecca C, An *Analysis of Multiskilled Labor Strategies in Construction,* Dissertation, The University of Texas, 1997.

Campbell, Gerard, *Cross-Utilization of Workers Whose Capabilities Differ,* Management Science v 45 n 5 1999 USA p 722-732.

Carley, Lynn Ann. *Worker's Attitudes Toward and Experiences with Multiskilling.* M.S. Thesis, University of Texas at Austin, Austin, TX., 1999.

Carmichael, H. Lome, and MacLeod, W. Bentley, *Multiskilling, Technical Change and the Japanese Firm,* The Economic Journal, pg. 142-160, January 1993.

Cass, Donald J., *Labor Productivity Impact of Varying Crew Levels,* 1992 AACE Transactions Volume 1.C2.1-C2.9.

Construction Industry Institute," Construction Industry Institute Model Plant Update", CII, Austin, TX, publication 2-2, November 1988.

Cross, Michael, *Flexibility and Integration at the Workplace,* Insights in Human Resource Management, v. 27 n. 4, pp.43-47, November 4, 1989.

Cross, Michael, *Multi-skilling brings cost and productivity benefits,* Training Plant Management, 11^{th} National Maintenance Engineering Conference, UK Dambrino, Richard, *Current Multiskilling Practices Survey,* December 9, 1996.

Denton, Keith D. *Multi-skilled Teams Replace Old Work Systems,* HR Magazine, v.37 n. 9, pp. 48-56, September 1992.

Gomar, J. *Assignment and Allocation Optimization of a Partially Multiskilled Workforce,* M.S. Thesis, University of Texas at Austin, 1999.

Hegazy, Tarek. *Optimization of Resource Allocation and Leveling using Genetic Algorithms,* ASCE Journal of Construction Engineering and Management, Vol. 125, No. 3, May/June 1999.

Li, Shirong, *New Approach for Optimization of Overall Construction Schedule,* ASCE Journal of Construction Engineering and Management, Vol. 122, No. 1, March 1995.

Liska, R. *Maintaining Skilled Construction Workers,* Material from Construction Industry Institute 1998 Conferences, Minneapolis, MN., 1998, SP 98-07.

Maloney, William F. and McFillen, James J., "Motivational Impact of Work Crews," *Journal of Construction Engineering and Management,* v. 113, n. 2 pg. 218, June 1987.

Rodriguez, A. *Planning and Scheduling a Multiskilled Workforce.* M.S. Thesis, University of Texas at Austin, Austin, TX., 1998.

Rogge, David F. *Foreman-Delay Surveys for Construction Sites.* PH.D Dissertation, University of Texas at Austin, Austin, TX. 1981.

Stanley, A. *Benefits, Impediments, and Limitations to Multi-skilling in Construction.* M.S. Thesis, University of Texas at Austin, Austin, TX., 1997.

The Business Roundtable (BRT). *Confronting the Skilled Construction Workforce Shortage.* Washington DC, 1997.

The Business Roundtable. *Construction Industry Cost Effectiveness Study, Summer Report.* New York, 1983.

Thomas, Randolph H., "Labor Productivity and Work Sampling: The Bottom Line," *Journal of Construction Engineering and Management,* v. 117, n.3, pp. 423-444, September 1991.

Thomas, Randolph H., Maloney, William F., Homer, R. Malcolm W., Smith, Gary R., Handa, Vir K., Sanders, Steve R., "Modeling Construction Labor Productivity," *Journal of Construction Engineering and Management,* v. 116, n. 4, pp. 705-726, December 1990.

Villalobos, J. *Implementation of Multiskilling in the Construction Industry.* M.S. Thesis, University of Texas at Austin, Austin, TX., 1997.

Williamson, Robert M., *Developing a Multi-Skill Maintenance Workforce,* Strategic Work Systems Company, Mill Spring, NC, 1994.

Williamson, Robert M., *Optimum Performance Through Multi-Skill Maintenance,* AIPE Facilities, March/April 1992.

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