Assignment and Allocation Optimization of Partially Multiskilled Workforce

Jorge E. Gomar[1]; Carl T. Haas[2]; and David P. Morton[3]

Abstract: Multiskilling is a workforce strategy that has been shown to reduce indirect labor costs, improve productivity, and reduce turnover. A multiskilled workforce is one in which the workers possess a range of skills that allow them to participate in more than one work process. In practice, they may work across craft boundaries. The success of multiskilling greatly relies on the foreman's ability to assign workers to appropriate tasks and to compose crews effectively. The foreman assigns tasks to workers according to their knowledge, capabilities, and experience on former projects. This research investigated the mechanics of allocating a multiskilled workforce and developed a linear programming model to help optimize the multiskilled workforce assignment and allocation process in a construction project, or between the projects of one company. It is concluded that the model will be most useful in conditions where full employment does not exist; however, it is also useful for short term allocation decisions. By running the model for various simulated scenarios, additional observations were made. For example, it is concluded that, for a capital project, the benefits of multiskilling are marginal beyond approximately a 20% concentration of multiskilled workers in a project workforce. Benefits to workers themselves become marginal after acquiring competency in two or three crafts. These observations have been confirmed by field experience. Extension of this model to allocation of multifunctional resources, such as construction equipment, should also be possible.

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Introduction

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). This trend will not soon change. To be competitive in the construction industry, it is necessary to consider other strategies to counterbalance 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 (Williamson 1992; Cross 1996; Burleson et al. 1998). Field studies have also indicated that multiskilling may benefit workers. Such benefits include longer employment duration, better qualifications resulting in increased employability, and increased job satisfaction (Stanley 1997; Rodriguez 1998; Carley 1999).

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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 longer durations 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 being replaced by an additional worker.

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. To obtain the maximum benefits from multiskilling, practitioners have stated that tools that help to 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.

Objectives

The objectives of this research were: (1) to develop a model to optimize the workforce resource allocation and assignment process of a partially multiskilled workforce; (2) to test and evaluate the model using the Construction Industry Institute (CII) Model Plant Data (Burleson et al. 1998); and (3) to use the model and the data to understand the mechanics and trade-offs of multiskilling.

Methodology

Previous research provides a general path toward potential improvements through the use of multiskilling. Literature in opera-

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tions research and decision sciences illuminates some fundamental labor allocation problems and optimization techniques for solving those problems. While useful references, none of the existing techniques were directly applicable.

These sources were used to help develop a model that optimizes the allocation process for a multiskilled workforce in construction. The Multiskilling Optimization Model for Allocation (MOMA) 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 multifunctional equipment, and used as a basis for analysis in the development of an economic model for a multiskilled workforce (Burleson et al. 1998). The optimization tests were conducted in the General Algebraic Modeling System (GAMS). GAMS (Brooke et al. 1992) is especially useful for handling large, complex optimization problems, which may require many revisions to establish an accurate model like the one developed by this research. The results of the tests were analyzed in order to understand the mechanics of multiskilling.

Background and Literature Review

This section presents background information that is necessary for understanding the rationale underlying the formulation of the model developed.

Multiskilling in Construction

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). 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 (Rogge 1981; Alfeld 1988; Thomas et al. 1990; Thomas 1991).

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 and McFillen (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 previous 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 millennium, it is a recurring one historically.

As stated earlier, multiskilling is a labor technique that addresses many of the above-stated problems. 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.

Previous research by CII (1988) has demonstrated that multiskilling has the potential of increasing average employment duration on a job by 18–47% and decreasing the necessary number of hires by up to 35% (Burleson et al. 1998). Other results in Burleson et al. (1998) indicate potential labor cost savings of 4.7% without any productivity increase in the labor force due to multiskilling.

Some believe that multiskilling also improves productivity due to the benefits stated above. 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 documented one.

A previous study (Rodriguez 1998) concluded that the success of multiskilling greatly relies on the superintendent's ability to assign workers to appropriate tasks and organize effective crews. The surveyed companies possess extensive databases in which the information regarding the skills and experience of workers are contained. However, these databases are rarely consulted as resources to assemble crews or to move labor between local or regional projects. They are primarily used for initial hiring. This process can be improved.

Another study based on a survey of over 1,000 workers in various crafts and geographic locations focused on the workers' attitudes towards and experiences with multiskilling (Carley 1999). 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. The majority of those surveyed believe that 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. They are willing to learn additional skills if they are compensated for the work by additional pay, benefits, challenging work assignments, and more responsibility.

Multiskilling In Related 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 (Alster 1989; Cross 1989; Denton 1992; Carmichael and MacLeod 1993; Williamson 1994). Other cited potential benefits include smaller crews, shorter equipment downtimes, and increased earnings for employees (Williamson 1992).

At least one researcher has suggested 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 (Cass 1992). In general, switching workers between crews and jobs decreases productivity through transaction costs and learning curve effects.

Brusco and Johns (1996) studied the staffing of a multiskilled workforce with varying levels of productivity using the opera-

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tions 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 multidepartment 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 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 degree of cross-training 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 models were used to 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 related to 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 1996; 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.

Model

Model Objectives

The objectives of the model developed by this research effort 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 background presented in the preceding section.

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. Because of these shortages, *minimizing the total number of worker-days* used in a project is one objective of the model developed. This is current practice, but it is also a logical requirement for the model to work properly.

Turnover on a construction site is partly a consequence of the shifts in skill requirements over the project duration. Turnover creates hiring costs. Turnover also creates learning costs. Multiskilling reduces turnover by providing a workforce with broader skill sets. Thus, it is clearly desirable for the model developed here to seek to *minimize the number of hires and thus fires* in the allocation and scheduling process.

''Switching'' is defined here as 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 ameliorate these consequences, it is important for the model to also *minimize the switching of workers from crew to crew*. Clearly some switching is a consequence of multiskilling. Trade-offs exist between the model's objectives and are captured by the structure of the model, which is described in the following sections.

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 turnover rate. The model seeks to address these shortcomings by *increasing the employment duration* of multiskilled workers. Doing so would provide them with higher annual income and an incentive to enter the industry (Carley 1999). To be precise, however, the model does not explicitly include ''employment duration'' in the objective function. This is in contrast to the previous three objectives discussed in this section, which are explicitly stated in the objective function. Instead, the model functions such that a by-product of having a multiskilled workforce, especially when hires and fires are discouraged, is that employment duration increases.

Model Capabilities

The mathematical formulation of MOMA is presented in Fig. 1. Its formulation as programmed in GAMS is included in Gomar (1999). A detailed description and exploration of the formulation of the model is beyond the scope of this paper; however, it can also be found in Gomar (1999). The MOMA model is capable of optimizing the labor allocation and assignment process of a partially multiskilled workforce. It works with a pool of workers whose skills are defined in a database. The model suggests what type and how many workers to hire over time, when to switch the workers to another activity, 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 a weighted sum of the number of days workers are hired, switching costs, and firing costs.

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

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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:
$DEMAND_{jt}$ demand of skill j on day t
P objective penalty weight on switching
F objective penalty weight on hires & fires

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

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

s.t.

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

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

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

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

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

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

Fig. 1. Mathematical formulation of Multiskilling Optimization Model for Allocation

$$\text{Minimize} \sum_{i\in I}\sum_{t\in T} W_{it} + P\cdot\sum_{i\in I}\sum_{j\in J_i}\sum_{t\in T}(Y_{p_{ijt}} + Yn_{ijt}) + F \cdot \sum_{i\in I}\sum_{t\in T} Z_{it}$$

The penalty factors in the objective function, P and F, are assigned scalar values that affect the last two terms. The P term is associated with switching, while the F term is associated with hires and fires. It is usually impossible to select numerical values for P and F a priori that accurately reflect a decision maker's aversion to incurring switching and hires and fires costs. Instead, such models are typically solved for a range of values of the penalty factors so that the trade-offs between the conflicting objectives are made clear. In addition, comparing the results obtained for ranges of P and F with current practice can be used to detect inefficiencies and/or implicit current values of P and F.

This model cannot capture 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 goals; it should be used as a tool to aid planning and not as a replacement of planners.

The model separates workers' allocation (hired) and workers' assignment (Fig. 2). The histogram in Fig. 2 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.

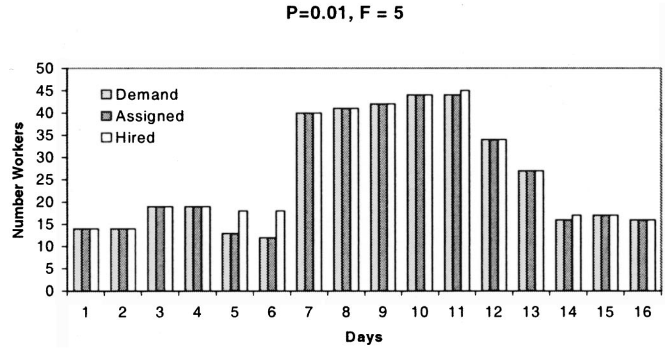

Fig. 2. Example of resource histogram of hired and assigned workers

This could cause workers to be hired and then fired and then rehired. 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 in a penalty function that forces the model to make the right decision in conserving workers or laying them off. Ultimately, this affects the set of hiring recommendations, which is the output of the model.

It can be observed from Fig. 2 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, 11, 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 the penalty value (F) that controls the cost of hiring and firing in the model. Lowering this value will result in more fires and rehires, 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 available in order to meet the constraints and optimize 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 multivariable 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. A sample cross section of the model output related to the simple example presented in Fig. 2 is presented in Table 1. It illustrates the assignment of workers to different jobs, switching from job to job, idle time, and hires and fires.

In Table 1, the upper subtable identifies all worker assignments, and the lower one identifies whether or not a worker is hired, kept, or fired. The upper subtable identifies the skills that a particular worker will use in a project. For example, the first two rows indicate that WORKER41 will use skill A from day one up to day three and will switch (highlighted by the bold box) to skill C from day four to day eight. 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 five and day six, but looking at the lower table it is seen that WORKER50 is hired and

Table 1. Output of Worker Assignments and Allocations from Multiskilling Optimization Model for Allocation

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

available. Idle time for this model means that a worker is not needed in any of the scheduled work assignments.

Analysis of Multiskilling

The MOMA 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 2). The tests were conducted by varying the percentage of multiskilled workers available from 0 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 2. 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

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 always continue to 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 using a single-skilled workforce (Burleson et al. 1998). The tests conducted on the Model Plant data were able to achieve a 2.3:1 average total to peak ratio for a single-skilled workforce. This ratio improved significantly with the addition of a multiskilled workforce, but the rate of improvement of this ratio diminished as the percentage of the multiskilled workforce was incremented (Fig. 3). For each increment of multiskilled workers, several tests were run with values for the 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 Fig. 3 represents the average of the results.

Selection of Multiskilled Workers versus Single-Skilled Workers

The model consistently selected multiskilled workers first during the initial days of the project, while the single-skilled workers

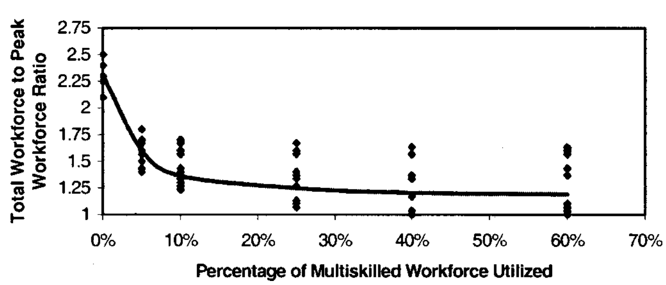

Fig. 3. Diminishing benefits from multiskilling

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Table 3. Average Selection Preference by Multiskilling Optimization Model for Allocation between Single-Skilled Workers (SS) and Multiskilled Workers (MS) with Different Percentages of Multiskilled Workforce (Percent MS)

	Selection preference	
Percent-multiskilled workforce	SS (%)	MS (%)
10	72	100
25	54	100
40	37	100
60	33	87

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 3 indicates the preferences of MOMA for selecting workers at different percentages of multiskilled workforces. The table represents average results for workforce combinations 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.

An important result from the model runs is that increased breadth gives the multiskilled workers job security by increasing their employment duration. Fig. 4 illustrates how the number of skills (essentially trades) 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 illustrates an interesting behavioral characteristic of the model: it is able to obtain optimal solutions without the necessity of utilizing the full breadth of skills of workers with many skills.

In runs of the model, an expected relationship between turnover (hires and fires) and idle time was demonstrated. Idle time is the difference between the ''Hired'' and ''Demand'' bars in a resource histogram, as in the example in Fig. 5. 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 would have been reduced. Experimental results clearly indicated that idle time decreases as the number of hires and fires increase and increases as hires and fires decrease. While this is rather obvious, it does help to validate the model. 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.

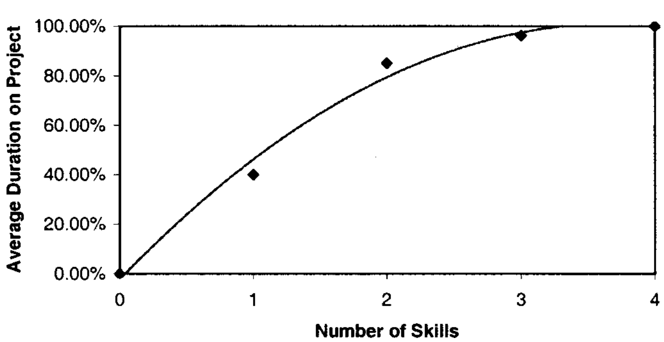

Fig. 4. Average duration of workers on project with respect to number of skills possessed

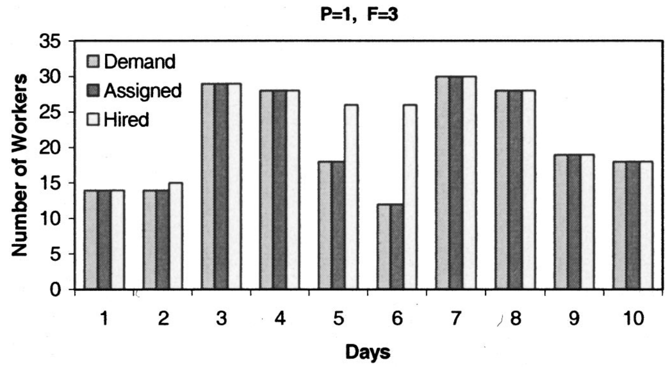

Fig. 5. Resource histogram results after assignment optimization of segment of CII Model Plant with 10% multiskilled workforce

Conclusions and Recommendations

Conclusions

A few 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. Additional benefits of multiskilling above a 10–20% partially multiskilled workforce are marginal; and
4. The benefits of increased participation and job employment duration for workers is marginal after they possess skills in two or three crafts.

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 reduced value. However, for short interval planning it can suggest activity assignments that minimize switching. It also can be used to set strategic targets for skill combinations and their demand volumes for classes of projects. Ultimately, the model could be extended to handle the allocation of multifunctional resources as well, such as skid steer, excavating, and lifting equipment.

Recommendations

The following recommendations can be made for future research:
1. The model should be field tested and its recommended hiring plans compared to actual construction project plans, to evaluate the potential of its application;
2. The model should be expanded to incorporate two or three basic skill levels in each area;
3. Tests should be run with different skill combinations that represent natural affinities, in order to evaluate the most effective combinations;
4. Values for the penalty factors need to be developed that model the true penalty costs in practice; and
5. Multiskilling percentage levels in the 0–10% range need to be examined.

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