PRODUCTION PLANNING & CONTROL, 1999, VOL. 10, NO. 6, 570–578

Integrated project operations and personnel scheduling with multiple labour classes

HESHAM K. ALFARES, JAMES E. BAILEY and WEN Y. LIN

Keywords project scheduling, personnel scheduling, integer programming, project management

Abstract. The main theme of this paper is improving project schedules by integrating the scheduling of project jobs and labour resources. An ILP model is presented of the integrated project operations and personnel scheduling problem with multiple labour categories. Traditionally, this problem is solved in two steps: first, operations are scheduled by solving the resource-constrained project scheduling problem; then, labour categories are scheduled by solving the personnel days-off scheduling problem. The proposed model combines the two stages into an integrated problem, which is solved in one step. Using 48 test problems, the two methods were compared in terms of total cost, labour cost and scheduling efficiency. The results clearly indicate that the integrated model outperforms the traditional two-step method.

Authors: H. K. Alfares, King Fahd University of Petroleum and Minerals, P.O. Box 2003, Dhahran 31261, Saudia Arabia, e-mail: hesham@ccse.kfupm.edu.sa, J. Bailey, Industrial & Management Systems Engineering Department, P.O. Box 875906, Arizona State University, Tempe, AZ 85287-5906, USA, and W. Y. Lin, America West Airlines, 4000 E. Sky Harbor Blvd., Phoenix, AZ 85034, USA.

HESHAM K. ALFARES is Assistant Professor at the Systems Engineering Department of King Fahd University of Petroleum & Minerals in Dhahran, Saudi Arabia. He received his PhD in industrial engineering from Arizona State University in 1991. His current research interests include project and labour scheduling, maintenance planning, and modelling and optimization of petrochemical systems. He has published a number of papers in these topics.

JAMES BAILEY is Professor and Associate Chair of Industrial Engineering at Arizona State University. He received his PhD in 1975 from Wayne State University in Detroit, Michigan. His current areas of research and teaching include production control, personnel scheduling, and effective product design methodologies. He has published a production control text and many papers on different topics.

WEN LIN is Senior Material Analyst for America West Airlines in Phoenix, Arizona. He received his PhD in 1993 from Arizona State University in Tempe, AZ. Prior to this, Dr Lin was Professor of Business Administration at National Pangtung Polytechnic Institute and Director of Graduate Programs in Management Science at Providence University in Taiwan. His current areas of research include material control modelling and personnel scheduling. He has published several papers in his research areas.

Production Planning & Control ISSN 0953–7287 print/ISSN 1366–5871 online © 1999 Taylor & Francis Ltd
http://www.tandf.co.uk/JNLS/ppc.htm
http://www.taylorandfrancis.com/JNLS/ppc.htm

1. Introduction

The significant effect of scheduling on project labour productivity has been widely recognized in the literature, e.g. Oglesby *et al.* (1989), and Thomas and Napolitan (1995). Oglesby *et al.* (1989) emphasized the importance of project scheduling, stating that completeness, accuracy and timeliness of project schedules can considerably improve project productivity. Traditionally, project operations (jobs) are scheduled first, fixing daily labour demands, then personnel are assigned to work shifts in order to satisfy these demands. As the two steps are interdependent, integrating them improves the efficiency of project schedules.

The major purpose of this paper is to present a model of the integrated project operations and personnel scheduling for multiple labour categories. First, the integer linear programming (ILP) model of the integrated multiple-resource scheduling (IMRS) problem is developed. Then the ILP models of the traditional two-step method are presented for both steps: (i) resource-constrained project scheduling; and (ii) manpower days-off scheduling. Subsequently, the new model is compared to the traditional two-step approach in terms of the total cost, labour cost and labour utilization. Finally, an analysis is performed to determine the factors that affect the IMRS's improvement over the two-step method.

2. Literature review

A project can be defined as a large-scale system of sequenced operations (also called jobs). Traditionally, project operations are scheduled first to determine each job's duration and start time, given precedence restrictions and resource limitations. The critical path method (CPM) for project scheduling assumes unlimited resource availability, but in the real world resources are always limited.

Many project scheduling techniques have been developed to include resource considerations. Davis (1973) categorized project scheduling problems into three types: (i) time/cost trade-off problems; (2) resource levelling or smoothing; and (iii) resource-constrained scheduling. Icmeli *et al.* (1993) added a fourth category: the payment scheduling problem, in which the objective is to maximize the net present value of project cash flows. This paper is concerned with resource-constrained project scheduling, with limited availability of multiple labour resources.

Elmaghraby (1977), Hiroaka (1980), and Talbot (1982) presented very similar ILP formulations of the resource-constrained project scheduling problem. These models schedule project operations with time/cost trade-off crashing opportunities. Dean *et al.* (1992) combined project scheduling with efficient allocation of labour demands. Recently, Alfares and Bailey (1997) presented a model of the integrated project task and labour scheduling for a single labour category. Of the many surveys of literature on resource-constrained project scheduling, the latest was compiled by Ozdamar and Ulusoy (1995).

Personnel scheduling is classified by Baker (1976) into three problems: (i) time-of-day or shift scheduling; (ii) day-of-week or days-off scheduling; and (iii) tour scheduling, which combines the first two. Tiberwala *et al.* (1972), Baker (1974), and Browne and Tiberwala (1975) formulated models in which only consecutive pairs of off days are allowed per week. Baker's (1976) ILP set covering model of personnel days-off scheduling allows the costs of different days-off shift patterns to vary, thus it can be used to minimize either the total number or total cost of workers assigned. Thompson (1990) included resource constraints in an LP model for shift scheduling with limited availability of employees. Tien and Kamiyama (1982), and Bedworth and Bailey (1987) provided comprehensive reviews of literature on labour scheduling.

3. Assumptions

The following assumptions apply both to the proposed IMRS model and to the traditional two-step model.

(1) As 1 day is the smallest time unit considered in both project scheduling and manpower days-off scheduling, it is the smallest time unit considered in this paper. Consequently, only a single (day) work shift is allowed per day.
(2) Only labour resources are considered in scheduling. However, the workforce is assumed to consist of multiple types of workers representing different crafts.
(3) Time and manpower requirements for each job (operation) are assumed to be given integer quantities, where the time is a decreasing function of manning level.
(4) Once a job is started on a given performance schedule (duration and associated start time), it must be completed without interruption on the same schedule.
(5) Only the seven weekly shift patterns with two consecutive off days per week are considered. As a weekend workday is paid at premium rate, the cost of each weekly shift pattern depends on the number of weekend workdays it contains.

(6) Once the project is started, the work on it continues uninterrupted, 7 days a week, until the project is completed.

4. The IMRS problem's ILP model

The following definitions are required to develop the IMRS model.

b_{wid} $\begin{cases} 1 & \text{if day } d \text{ is a work-day for shift pattern } i \text{ of week } w \\ 0 & \text{otherwise} \end{cases}$

C_{ik} weekly cost per category k worker on shift pattern i

CP project critical path length (minimum duration) in days

DD project due date (maximum duration) in days

ES_j earliest start day of job (operation) j

$\mathcal{J}$ total number of jobs in the project

K number of labour categories

L set of the last jobs in the project which have no successors

LS_{jt} latest start day of job j when its time (duration) is t, as determined by the due date DD

M_{jtk} number of class k workers required per day for job j when its duration is t days

OH project overhead cost per day

P_j set of all jobs immediately preceding job j

T_j set of all possible durations of job j (in days)

W project due date in weeks = (smallest integer $\geq DD/7$)

WF_k workforce size, i.e. total number of category k workers available

4.1. *Decision variables*

PT project duration in days, $CP \leq PT \leq DD$ *and* integer

X_{jdt} $\begin{cases} 1 & \text{if job } j \text{ is started on day } d \text{ with duration } t, \\ 0 & \text{otherwise} \end{cases}$
$j = 1, \ldots, \mathcal{J}$, $ES_j \leq d \leq LS_{jt}$, $t \in T_j$

Y_{wik} number of category k workers assigned to days-off shift pattern i in week w, $Y_{wik} \geq 0$ and integer, $w = 1, \ldots, W$, $i = 1, \ldots, 7$, $k = 1, \ldots, K$

4.2. *The objective function (minimizing total cost)*

The objective sought is minimizing the total project cost, which is the sum of two components. The first component is the total labour cost, which is the sum of weekly costs C_{ik} of each days-off shift pattern i for labour class k times the number of workers assigned to it Y_{wik} in every week w. The second component is the total overhead cost, which is the daily overhead cost OH multiplied by project duration in days PT. Therefore, the objective function is written as

$$\text{Minimize} \sum_{w=1}^{W} \sum_{i=1}^{7} \sum_{k=1}^{K} C_{ik} * Y_{wik} + OH * PT \qquad (1)$$

The objective function is minimized subject to the following constraints.

4.3. *Unique job performance constraints*

Each job (operation) in the project must be performed once and only once. A unique performance schedule (duration and start time) must be chosen. Thus, only one variable X_{jdt} associated with each job must equal one.

$$\sum_{d=ES_j}^{LS_{jt}} \sum_{\cup t \in T_j} X_{jdt} = 1, \quad j = 1, \ldots, \mathcal{J} \qquad (2)$$

Elmaghraby (1977) proposed imposing unique job performance constraints (2) only on the last set of jobs with no successors L. The transitivity of the following precedence constraints (3), he explained, would force the remaining jobs to be uniquely performed. Although this approach reduces the number of ILP constraints, it increases solution time. Computational experience by Alfares (1991) showed that it is more efficient to restrict all the jobs in the project. Thus, unique performance constraints (2) are imposed on all jobs in the given project.

4.4. *Precedence constraints*

A job start day d_j must be later than the completion day of any immediate predecessor $(d_p + t_p - 1)$. Because the job can start, at the earliest, on the day following its predecessor's completion day $(d_p + t_p)$, this restriction is expressed as

$$\sum_{d=ES_p}^{LS_{pt}} \sum_{\cup t \in T_p} (d + t) X_{pdt} \leq \sum_{d=ES_j}^{LS_{jt}} \sum_{\cup t \in T_j} d^* X_{jdt},$$
$$\cup p \in P_j, j = 1, \ldots, \mathcal{J} \qquad (3)$$

For any job j, the number of precedence constraints (3) is equal to the number of immediate predecessors NP_j. Hiroaka (1980) developed an alternative formulation in which only one precedence constraint is needed for each job with predecessors, regardless of the number of immediate predecessors. Unlike constraints (3) above, Hiroaka's precedence constraints are not transitive, thus when they are used all the jobs in the project must be restricted by the unique performance constraints (2). Although Hiroaka's formulation uses fewer precedence constraints, Alfares's (1991) experience showed the above conventional formulation to be computationally more efficient.

4.5. *Project completion constraints*

Project duration in days PT equals the latest job completion day $(d + t - 1)$ among the set *of* last jobs without successors L. The constraints are written as

$$\sum_{d=ES_j}^{LS_{jt}} \sum_{\cup t \in T_j} (d + t - 1) X_{jdt} \leq PT, \quad \cup j \in L \tag{4}$$

4.6. *Weekly labour (resource) constraints*

In each week w, the total number of workers assigned for each category k cannot exceed the size of the available workforce in that category WF_k. Because the availability of each resource (i.e. labour category) is limited, the following resource constraints must be included in the model

$$\sum_{i=1}^{7} Y_{wik} \leq WF_k, \quad w = 1, \ldots, W, k = 1, \ldots, K \tag{5}$$

4.7. *Manpower scheduling constraints*

For each day of the project's duration, the total number of workers assigned to each category must be greater than or equal to the sum of the required labour of all jobs that are active on that day. Assuming that a job j is active on day d if it has been started in day q (i.e. completed on day $q + t - 1$), then

$$q \leq d \leq q + t - 1 \tag{6}$$

rearranging,

$$d - t + 1 \leq q \leq d \tag{7}$$

But as q is the job start day, the definition of X_{jqt} dictates that

$$ES_j \leq q \leq LS_{jt} \tag{8}$$

The combination of equations (7) and (8) yields

$$\max(d - t + 1, ES_j) \leq q \leq \min(d, LS_{jt}) \tag{9}$$

Because a job j is active on day d only if its start time q satisfies equation (9), daily manpower scheduling constraints can be written as

$$\sum_{j=1}^{J} \sum_{\cup t \in T_j} \sum_{q=\max(d-t+1, ES_j)}^{\min(d, LS_{jt})} M_{jtk} X_{jqt} \leq \sum_{w=1}^{W} \sum_{i=1}^{7} b_{wid} Y_{wik},$$
$$k = 1, \ldots, K, d = 1, \ldots, DD \tag{10}$$

The values of b_{wid} correspond to the seven weekly shift patterns with two consecutive off days per week. Let shift pattern i be off on days $(i, i + 1)$ for $i = 1, \ldots, 6$ and days $(7, 1)$ for $i = 7$, where day $1 =$ Monday and day $7 =$ Sunday.

5. The two-step method

Operations and labour scheduling for projects are usually performed in two separate steps. In the first step, jobs (operations) are scheduled using resource-constrained project scheduling techniques. This step determines job start times and durations, and thus the daily labour demands. In the second step, labour resources are scheduled to satisfy these demands, using manpower days-off scheduling techniques. This step determines the number of workers of each labour category assigned to each days-off shift pattern in every week. The ILP models of the two steps are presented below.

5.1. *Step 1. Project operations scheduling*

The objective at this stage is to minimize the cost of total labour man-day demands plus overheads. This is expressed as follows:

$$\text{Minimize} \sum_{k=1}^{K} LC_k \sum_{j=1}^{J} \sum_{d=ES_j}^{LS_{jt}} \sum_{\cup t \in T_j} t_j * M_{jtk} * X_{jdt} + OH * PT \tag{11}$$

where: $LC_k =$ unit cost of class k labour $=$ regular pay per non-weekend man-day.

Objective function (11) is subjected to constraints representing: unique job performance (2), precedence (3), and project completion (4). In addition, the following labour resource constraints must be included to ensure that daily labour demand does not exceed the workforce size for each labour category.

$$\sum_{j=1}^{J} \sum_{\cup t \in T_j} \sum_{q=\max(d-t+1, ES_j)}^{\min(d, LS_{jt})} M_{jtk} X_{jqt} \leq WF_k,$$

$$k = 1, \ldots, K, d = 1, \ldots, DD \qquad (12)$$

5.2. *Step 2. Project labour scheduling*

Having fixed the duration and start time of each operation, labour must now be assigned to perform these operations. What needs to be determined is the number of workers of different labour categories assigned to each of the seven days-off shift patterns in each week. Therefore, the following weekly days-off scheduling problem must be solved once for each week w and every labour category k. The objective (13) is to minimize the weekly labour cost, subject to daily demand constraints (14).

$$\text{Minimize} \sum_{i=1}^{7} C_{ik} * Y_{wik} \qquad (13)$$

subject to

$$\sum_{i=1}^{7} a_{id} Y_{wik} \geq R_{dk}, \quad d = 1, \ldots, 7 \qquad (14)$$

where

$$a_{id} = \begin{cases} 1 & \text{if day } d \text{ is a work-day for shift pattern } i \\ 0 & \text{otherwise} \end{cases}$$

R_{dk} = total demand for labour of category k on day d = left-hand side of constraint (12)

6. Computational results

The proposed integrated multiple-resouce scheduling (IMRS) model was compared with the traditional two-step model in terms of total cost, labour cost and labour utilization. A set of 48 test problems was carefully designed to allow the comparison over a variety of project types. The factors that affect the relative performance of the proposed scheduling procedure are naturally those with the greatest impact on the size of the ILP model, i.e. (i) number of jobs in the project J; (ii) average number of predecessors per job P; (iii) average number of crashing opportunities C, e.g. feasible staff-size/job-duration combinations; and (iv) average job duration T.

By allowing two values for each of the above four factors, $2^4 = 16$ combinations were possible. The number of jobs J considered was either 6 or 8, and the average number of predecessors P was either 0.6 or 1.0. Twelve (12) networks were constructed, shown in figure 1, such that a set of three networks was developed for each of the four combinations of P and J. By varying job durations and crashing opportunities, each network in turn was used to generate four test problems. The problems involved either 1.5 or 2.0 for the average number of crashing opportunities C, and either 4 or 8 days for average job duration T.

To solve the 48 test problems, two programs were written in C/C++ programming language for any IBM or compatible DOS-based personal computer. One program used the proposed integrated solution method, while the other employed the two-step method. In either case, the C/C++ code was used to develop ILP coefficient matrices that represented the problems inside the EXCEL spreadsheet. LINDO's linear programming software spreadsheet version 'What's Best' was used to optimally solve the models. Table 1 summarizes the characteristics of the 48 test problems, and the percentage improvement in total cost, labour cost and labour utilization obtained by using the IMRS model over the two-step model.

6.1. *Total project cost*

Total project cost has been defined in equation (1) as the sum of labour and overhead costs. For the two-step method, the labour cost obtained by equation (15) is summed over all weeks and labour classes, then added to the overhead cost obtained from equation (13). In terms of total cost, the integrated method performed better than the two-step method in all but two cases, where it did equally well. The per cent savings produced by the integrated method ranged from 0.00% to 19.36%, with an average of 5.65% and standard deviation of 4.46%. Because the problem set was designed over a variety of test conditions, it is hard to argue that the data are normally distributed. However, the per cent savings of the integrated method are normally distributed and tests of significance are possible. The hypothesis that improvement in total cost is equal to zero was easily rejected at a significance level α of 0.01.

6.2. *Labour cost*

The labour costs obtained by the integrated method were also lower than those produced by the two-step method in 46 problems. In the two remaining problems, the costs obtained by the two methods were identical.

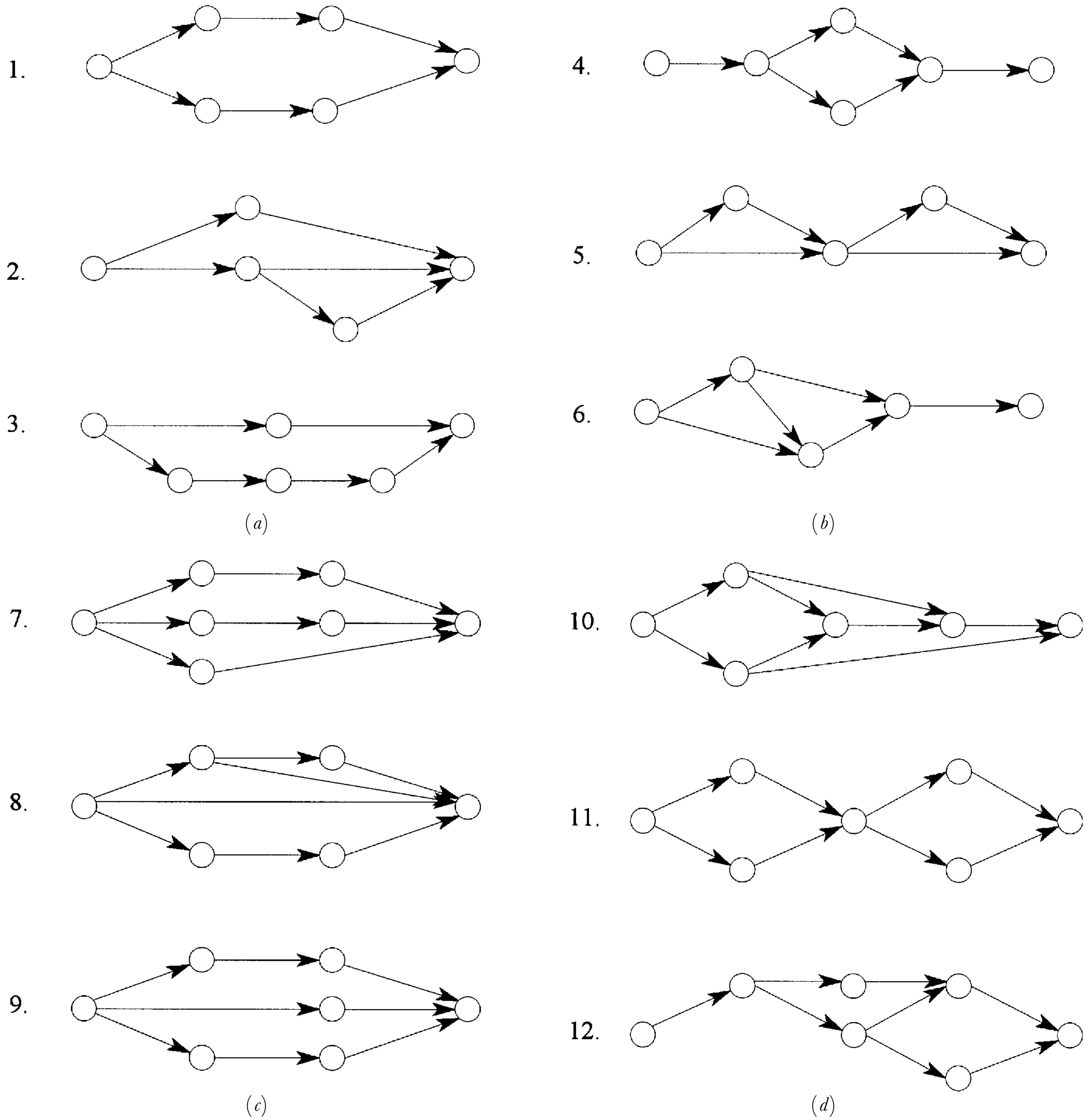

Figure 1. (*a*) Problem networks with (a) $\mathcal{J} = 6$ and $P = 0.6$. (*b*) $\mathcal{J} = 6$ and $P = 1.0$. (*c*) $\mathcal{J} = 8$ and $P = 0.6$. (*d*) $\mathcal{J} = 8$ and $P = 1.0$.

The per cent savings in labour cost with respect to the two-step method ranged from 0.00 to 42.56%, with an average of 12.71% and standard deviation of 8.81%. The hypothesis that per cent improvement in labour cost is equal to zero was easily rejected at a significance level α of 0.01.

6.3. *Labour utilization*

Labour utilization is a measure of scheduling efficiency. Because efficiency is the ratio of output (productive labour time) to input (total labour time), utilization is defined as:

Table 1. Performance improvement of the integrated method over the two-step method.

Prob. no.	Net. no.	J	$\bar{P}$	$\bar{C}$	$\bar{T}$	Total cost % cut	Labour cost % cut	Utilization % up
1	1	6	0.6	1.5	4	15.50	29.06	26.53
2	1	6	0.6	1.5	8	0.00	0.00	0.00
3	1	6	0.6	2	4	3.22	6.45	4.93
4	1	6	0.6	2	8	1.55	3.34	5.38
5	2	6	0.6	1.5	4	7.00	13.04	15.97
6	2	6	0.6	1.5	8	7.00	15.37	16.42
7	2	6	0.6	2	4	12.26	25.51	25.08
8	2	6	0.6	2	8	5.40	12.13	12.36
9	3	6	0.6	1.5	4	1.46	3.19	3.62
10	3	6	0.6	1.5	8	9.78	22.30	19.89
11	3	6	0.6	2	4	12.49	26.50	24.61
12	3	6	0.6	2	8	5.14	12.03	6.92
13	4	6	1	1.5	4	0.86	2.03	7.84
14	4	6	1	1.5	8	0.34	1.09	1.09
15	4	6	1	2	4	5.55	12.17	10.94
16	4	6	1	2	8	0.00	0.00	0.00
17	5	6	1	1.5	4	19.36	42.56	41.96
18	5	6	1	1.5	8	1.06	2.61	2.69
19	5	6	1	2	4	9.58	22.69	23.33
20	5	6	1	2	8	7.44	21.38	17.55
21	6	6	1	1.5	4	4.63	11.36	11.36
22	6	6	1	1.5	8	4.29	11.73	12.40
23	6	6	1	2	4	3.76	10.12	6.95
24	6	6	1	2	8	3.47	8.90	14.09
25	7	8	0.6	1.5	4	7.41	19.07	15.51
26	7	8	0.6	1.5	8	2.32	4.71	5.42
27	7	8	0.6	2	4	6.72	12.08	13.74
28	7	8	0.6	2	8	5.72	18.10	11.86
29	8	8	0.6	1.5	4	3.99	7.13	3.64
30	8	8	0.6	1.5	8	2.10	7.81	5.07
31	8	8	0.6	2	4	6.53	11.73	13.60
32	8	8	0.6	2	8	4.18	16.17	13.83
33	9	8	0.6	1.5	4	10.23	22.86	22.74
34	9	8	0.6	1.5	8	1.31	8.80	5.95
35	9	8	0.6	2	4	11.66	26.19	26.03
36	9	8	0.6	2	8	5.30	21.49	13.18
37	10	8	1	1.5	4	4.60	8.78	7.76
38	10	8	1	1.5	8	8.10	15.59	15.51
39	10	8	1	2	4	16.10	15.77	15.30
40	10	8	1	2	8	5.67	10.57	10.53
41	11	8	1	1.5	4	3.31	6.67	7.92
42	11	8	1	1.5	8	0.16	0.44	0.41
43	11	8	1	2	4	5.90	12.32	12.41
44	11	8	1	2	8	1.23	7.85	8.04
45	12	8	1	1.5	4	5.98	12.37	13.17
46	12	8	1	1.5	8	1.39	3.85	4.25
47	12	8	1	2	4	9.09	17.99	16.00
48	12	8	1	2	8	1.04	9.08	2.03

$$\text{Utilization} = \frac{\text{total required mandays}}{\text{total assigned mandays}} \tag{15}$$

Labour utilization percentages obtained by the integrated method were higher than those produced by the two-step method in all but two problems. In these two cases, the values obtained by the two methods were identical. The percent labour utilization of the two-step method ranged from 55.4% to 89.5%, with an average of 79.2% and standard deviation of 8.7%. For the integrated method, the per cent labour utilization ranged from 76.2% to 99.5%, with an average of 93.2% and

Table 2. Summary of the F-statistics obtained from the ANOVA tests.

Factor	Total cost	Labour cost	Labour utilization
$\bar{J}$			−21.24
$\bar{P}$		−54.83	−21.90
$\bar{C}$	+ 15.32	+ 42.78	+ 15.92
$\bar{T}$	−73.40	−186.59	−254.13

standard deviation of 8.0%. The integrated method outperformed the two-step method, on average, by 18.7%. The standard deviation of the relative difference in labour utilization was 12.9%. The hypothesis that per cent improvement in labour utilization is equal to zero was easily rejected at a significance level α of 0.01.

6.4. *Analysis of variance*

The four factors considered in designing the test problems are: (i) the number of jobs in the project $\bar{J}$; (ii) the average number of predecessors per job $\bar{P}$; (iii) the average number of crashing opportunities $\bar{C}$; and (iv) the average job duration $\bar{T}$. Each one of these four factors had two possible values, thus we had a 2^4 experiment. Analysis of variance (ANOVA) was carried out in order to examine the effect of each factor on the performance of the proposed integrated method. Table 2 summarizes the results, showing the F-statistics that result from the ANOVA. The sign of the F-statistic indicates whether the correlation is positive or negative, while the magnitude corresponds to the relative impact of each factor.

Table 2 shows that factors $\bar{C}$ and $\bar{T}$ have the most significant effect on the relative performance of the integrated method, as compared to the two-step method. The performance of the integrated solution improves as factor $\bar{C}$ increases, and deteriorates as factor $\bar{T}$ increases. To a lesser degree, the performance relatively deteriorates as either factor $\bar{J}$ or $\bar{P}$ increases.

7. Conclusions

A new ILP model integrating the scheduling of project operations and multiple labour resources has been presented. The integrated multi-resource scheduling (IMRS) model is able to produce significant savings when compared to the traditional two-step method. Currently, project operations are scheduled first, fixing daily labour demands, then workers are scheduled to satisfy these demands. By allowing the simultaneous scheduling of operations and labour categories, the proposed model minimizes the project labour cost. The model achieves its objective by scheduling project operations in a way that results in the most efficient assignment of labour resources. By maximizing the efficiency of labour scheduling, the integrated method ultimately improves labour productivity.

Using 48 test problems, the integrated and two-step methods were compared in terms of three perfomance measures: total cost, labour cost and labour utilization. On average, the integrated method yielded 5.7% savings in total cost, 12.7% savings in labour cost, and 18.7% improvement in labour utilization. It can be concluded that integrated scheduling of operations and labour resources can lead to lower-cost and higher-productivity projects.

It appears worthwile to pursue several new, related research avenues in the future. First, the computational difficulty of the integrated problem could be reduced by using either heuristic rules, decomposition approaches, e.g. dynamic progrmming, or a combination of both. Another extension would be to include non-monetary considerations in the objective function. For example, employee satisfaction, schedule smoothness and robustness (i.e. relative insensitivity to unpredictable changes). Finally, stochastic elements could be introduced by assuming that time and labour requirements are probabilistic variables.

References

Alfares, H. K., 1991, Integrated project activities and manpower scheduling. Unpublished PhD dissertation, Arizona State University, Tempe, AZ 85287-5906, USA.

Alfares, H. K., and Bailey, J. E., 1997, Integrated project task and manpower scheduling. *IIE Transactions*, **29**, 711–718.

Baker, K. R., 1974, Scheduling a full-time workforce to meet cyclic staffing requirements. *Management Science*, **20**, 1561–1568.

Baker, K. R., 1976, Workforce allocation in cyclical scheduling problems: A survey. *Operational Research Quarterly*, **27**, 155–167.

Bedworth, D. D., and Bailey, J. E., 1987, *Integrated Production Control Systems* (New York: Wiley), pp. 387–420.

Browne, J. E., and Tiberwala, R. K., 1975, Manpower scheduling. *Industrial Engineering*, **7**, 22–23.

Davis, E. W., 1973, Project scheduling under resource constraints: historical review and categorization of procedures. *AIIE Transactions*, **5**, 297–313.

Dean, B. V., Denzler, D. R., and Watkins, J. J., 1992, Multiproject staff scheduling with variable resource constraints. *IEEE Transactions on Engineering Management*, **39**, 59–72.

Elmaghraby, S. E., 1977, *Activity Networks: Project Planning and Control by Network Models* (New York: Wiley), pp. 173–185.

Hiroaka, T., 1980, Multiproject scheduling with resource constraints. *Bulletin of the Japanese Society of Mechanical Engineers*, **23**, 1929–1936.

Icmeli, O., Erenguk, S. S., and Zappe, C. J., 1993, Project scheduling problems: a survey. *International Journal of Operations & Production Management*, **13**, 80–91.

Lin, W. Y., 1993, A model of the integrated multiple resources project and personnel scheduling problems. Unpublished PhD dissertation, Arizona State University, Tempe, AZ 85287-5906, USA.

Oglesby, C. H., Parker, H. W., and Howell, G. A., 1989, *Productivity Improvement in Construction* (New York: McGraw-Hill), p. 442.

Ozdamar, L., and Ulusoy, G., 1995, A survey on the resource-constrained project scheduling problem. *IIE Transactions*, **27**, 574–586.

Talbot, F. B., 1982, Resource-constrained project scheduling with time-resource tradeoffs: the non-preemptive case. *Management Science*, **28**, 1197–1210.

Thomas, H. R., and Napolitan, C. L., 1995, Quantitative effects of construction changes on labor productivity. *Journal of Construction Engineering & Management*, **121**, 290–296.

Thompson, G. M., 1990, Shift scheduling in services when employees have limited availability: An LP approach. *Journal of Operations Management*, **9**, 352–370.

Tiberwala, R., Philippe, D., and Browne, J., 1972, Optimal scheduling of two consecutive idle periods. *Management Science*, **19**, 71–75.

Tien, J. M., and Kamiyama, A., 1982, On manpower scheduling algorithms. *SIAM Review*, **24**, 275–287.