NEW HEURISTICS FOR SCHEDULING SINGLE CONSTRAINED RESOURCE PROJECTS

M. A. Shouman*, A.Z. Ghafagy, M.A. Zaghloul** and A. A. Bou-Shaala*****

*Industrial Engineering Department, Faculty of Engineering, Zagazig University.
** Production Engineering Department, Faculty of Engineering, Suez Canal University.
***Industrial Engineering Department, Faculty of Engineering, Garyounis University.

ABSTRACT

The heuristic decision rules used for project scheduling will vary depending upon the project's size, complexity, duration, personnel, and owner requirements. In the current article, the most common heuristics that have been shown to achieve optimal or near-optimal solutions for single constrained resource projects are presented. Also, new developed heuristics and measures for project's complexity and scheduling performance are presented. The new measures show better sensitivity for both project complexity and scheduling performance. The developed heuristics have been studied with the project's complexity for a set of fifty projects. The developed heuristics show better results for scheduling process than common rules. The heuristics that will perform the best for each project complexity are introduced. General remarks, and conclusions are highlighted.

Keywords: Projects scheduling - Resource allocation - Constrained resources

INTRODUCTION, LITERATURE REVIEW, AND WORK SCOPE

Unfortunately, no simple heuristic criterion has been found to perform well for a wide variety of project network characteristics, and resource levels. This is because the success of a certain specified heuristic depends mainly on the project characteristics. Hence, there is still no such procedure, which is considered to be computationally-feasible for the large and complex projects which occur in practice. And since most success to date has been found in the application of heuristic techniques, research on heuristic solution procedures has been still popular. Three quantitative measures related to the project duration have been developed by Badiru [1] as measuring performance criteria to compare the project scheduling heuristics. The comparative experiment indicates that heuristics perform almost equally well for small projects while their performance varies considerably for large projects. A multi-objective management perspective has been used to arrive at schedules for the best utilization of scarce resources for multiple project-multiple resource constrained scheduling by Mohantly and Sidiq [2]. The analysis is accomplished by means of integer-programming and simulation. Multiple performance measures are used to establish the validity of each technique. Deckro *et al.* [3] developed the use of a decomposition algorithm in solving a resource limited, multi-project scheduling problem. The decomposition approach offers two distinct advantages over a direct optimization approach; the ability to realistically solve large scale problems and the option of using the decomposition approach as a heuristic. Nguyen and Stone [4] presented a multi-period mini-max resource allocation model in which the resources are storable and substitutable. This model uses primal-dual algorithm which was efficiently implemented using maximum flow algorithm and is capable of handling large scale projects. Lee *et al.* [5] focuses on the presentation of an integer programming model and a sub-optimization procedure for solving resource constrained scheduling problem. It provides an efficient integer programming formulation of hybrid resource. Ouali *et al.* [6] deals with a resource assignment modeling approach into a multi-project management context. The approach divides the resource assignment complexity into three levels, the structural one, the quantitative one, and qualitative one. Each level deals with one main constraint and uses appropriate modeling tools. A new approach for resource scheduling using genetic algorithms (GA) is presented by Chan *et al.* [7]. The methodology does not depend on any set of heuristic rules. Instead, its strength lies in the selection and recombination of (GA) to learn the domain of the specific project. The model is able to evolve improved schedules. Lorterapong *et al.* [8] presents a scheduling method based on a Fuzzy theory. The proposed method incorporates a number of new techniques that facilitate the interpretation of Fuzzy results generated, the representation of imprecise activity durations, and the calculation of scheduling parameters. Samules *et al.* [9] advised a construction management program that schedules manpower and controls costs of construction representatives. This program includes three phases; the planning phase forecasts future construction representative needs for the agency wide effort, the staffing phase schedules and assigns personnel to specific projects, and the monitoring phase furnishes performance and cost reports that compare actual results with the staffing estimates. Pocock *et al.* [10] developed a method for measuring a project degree of interaction (DOI) and verifies the relationship between (DOI) and performance indicators such as cost growth, schedule growth, and number of modifications. The results indicate that the projects with low DOI have a wide range of cost, schedule growth, and number of modifications, while projects with high DOI tend to have better and more consistent performance indicators. Russel *et al.* [11] describes a process where by owner, engineer, and construction contractor organization can use continuos or time dependent variable to predict project cost and schedules outcomes from start of detailed design through construction completion. A new approach to schedule projects of single constrained resource consideration is suggested by Shouman [12]. In this approach, the excess resources under the available limit are utilized in the compression of some project activities such that the resource bound is not exceeded. The reported results show that an increase of the utilization of the available resources has been achieved and the output schedules are the best for all the considered heuristics. Abourizk *et al.* [13] advised a combined simulation model to achieve more accurate and flexible modeling of random process affecting construction progress. In this model, the project schedule prepared by CPM is transferred into a process interaction-discrete event simulation model then combined with a continuos change weather process in the same model. A branch and bound procedure is proposed by Erik *et al.* [14] for scheduling project activities subjected to precedence diagramming type of precedence relations, ready times, due dates, and variable multiple resource availability constraints, where the objective is to minimize project duration. The procedure is based on a depth-first solution strategy in which nodes in the solution tree represent resource and precedence feasible partial schedules. A new model that adequately integrates the means of LOB and CPM in a mixed integer programming for resource allocation in repetitive projects has been introduced by Korish *et al.* [15]. The virtue of the suggested model lies in its ability to maintain work continuity in the repetitive activities. A new scheduling system based on statistical simulation is discussed by Senior *et al.* [16]. The system called project integrated cyclic analysis of serial system operations. (PICASSO), blends and enhances two existing techniques, namely, CPM and the cyclic operations network (CYCLONE) simulation. The model allows an explicit modeling of resource interaction and the formulation of complex resource sharing patterns, with its schedules automatically leveled to the availability of any number of resources. It has been concluded from the presented solution procedures that no suggested heuristics, for scheduling the constrained single resource problem, directly correlate the project complexity (characteristics, number of critical activities, single critical path or multiple critical paths, and the ratio between resource requirements and resource availability) with the developed heuristic rules of scheduling. The main objective of the present work, is to introduce new heuristics as scheduling criteria. These heuristics depend mainly on the project characteristics and will be studied with the project complexity classes to clarify their effectiveness on project completion.

NEW MEASURES FOR COMPLEXITY AND PERFORMANCE

The measurement of the "complexity" of projects by quantitative and qualitative factors are needed in order to estimate the computing requirements and/or to validly compare alternative heuristic procedures. Evidently, a choice between two proposed algorithms, or the determination of the efficiency of a particular algorithm, would be greatly facilitated if there exists a measure of network complexity. Table 1 gives a bird's eye view of the proposed measures mentioned in References 1 and 17. The suggested measure of Pascoe, Davies, and Kaimann rely totally on the account of the activities and nodes in the network. Since it is easy to construct networks of equal number of arcs and nodes but with varying degrees of difficulty in analysis, we fail to see how these measures can discriminate among them.

Table 1 Summary of measures of network complexity.

Coefficient of network complexity		
CNC(P) = A/N	Pascoe	[18]
CNC(D) = 2(A-N+1)/(N-1)(N-2)	Davies	[19]
CNC(K) = A^2/ N	Kaimann	[20]
Total activity density -T-density $\sum_N$ max. {0, number of predecessors - number of successors}	Johnson	[21]
Average activity density (T-density)/N	Patterson	[22]
$\rho_{mn} = q_n / PL_{mn}$ m=1,2,...,M, n=1,2,.., N	Padiru	[1]
$\phi_m = \sum_{n=1}^{N} \rho_{IJ}$ m=1,2,....,M	Padiru	[1]
$S_{mn} = ((PL_{mn} - q_n)/q_n)*100$ m=1,2,...,M n=1,2,..,N	Padiru	[1]
CNC(B) = (P/CP) { 1 - (1/A) $\sum_{i=1}^{A} t_i + \sum_{J=1}^{R} (\sum^{A} t_i r_{iJ} / RA_J)$ }	Padiru	[1]

Where:

CNC : coefficient of network complexity.
A : number of activities in the network.
N : number of nodes.
t_i : expected duration of activity i.
R : number of resource types .
r_{ij} : units of resource j for activity i.
RA_J : maximum number of resource available .
CP : project duration with no resource constraint .
P : maximum number of immediate predecessors in the network.
ρ_{mn} : the efficiency ratio for rule (m) under test problem (n).
q_n : min_m (PL_{mn}) minimum project duration observed for test problem (n).
RL_{mn}: project duration for test problem (n).
M : number of scheduling rules considered.
N : number of test problems.
ϕ_m : sums of ρ_{mn}.

$$CNC(PR)=[W/(1-Ac/A)]\ [(P/CP)\ \{1-(1/A) * \sum_{i=1}^{A} t_i + \sum_{J=1}^{R} (\sum^{A} t_i r_{iJ} / RA_J)\}] \quad (1)$$

Where
W : number of critical paths.
Ac: number of critical activities.

The proposed measure is more sensitive to the changes in the network data. The increase of critical paths and critical activities will increase the network complexity. The degree of sensitivity of the proposed measure has been tested and evaluated against the other measures of complexity for the considered fifty projects under consideration of the current work and gave accurate quantified results in comparing with other measures of complexity. However, for the proposed measure, when Ac equals A then W equals to unity and the project will be serial structure in its activities and the proposed measure transforms to Badiru's measure. The main privilege of the proposed measure is that, it considers size, shape, logic characteristic, time characteristics, resource demands, and availability as well as number of critical paths and activities. The resource availability for the problem under consideration is less than the amounts required during the project execution phase. In the current study, the minimum resource required to execute the project is the maximum value required by any activity in the project network [23], while the resource level at which the project will be executed at a constraint phase is determined according to a certain procedure. This procedure depends mainly on the Average Resource Utilization and Scheduling Efficiency (ARUSE) which is proposed as performance measure in the current study.

$$ARSUE = (RU + SE)/2 \quad (2)$$

where RU is the resource utilization and SE is the resource-constrained scheduling efficiency. Both RU and SE are calculated as:

The total activity density and average activity density as coefficients of network complexity consider only the maximum difference between the predecessor and successor activities allover the network nodes ignoring all the other network characteristics (shape, size, duration, resource, ..etc.). The quantitative measure presented by Padiru [1] is more sensitive than the other measures. In this measure, the maximum number of immediate predecessors (P) is a multiplicative factor that increases the complexity and potential for bottlenecks in a project network. The term (1-1/A) is a fractional measure (between 0 and 1) that indicates the time intensity or work content of the project. As A increases, the quantity (1-1/A) increases, and a larger fraction of the total time requirement sum of (t_i) is charged to the network complexity. Conversely, as A decreases, the network complexity decreases proportionately with total time requirement. The sum of $t_i r_{ij}$ indicates the time-based consumption of a given resource type j relative to the maximum availability. The term is summed over all the different resource types. Having CP duration in the denominator helps to express the complexity as a dimensionless quantity by canceling out the time units in the numerator. In addition it gives the network complexity per unit of total project duration. In the current study and in order to make this measure more sensitive for project complexity, two parameters having a great influence on the degree of complexity of the project network, are added to this measure. These parameters are: the number of critical activities and the number of critical paths of the project network where the increase of these parameters will increase the complexity of project scheduling. The proposed measure is defined as:

$$RU=\sum_{i=1}^{N}((\sum_{J=1}^{J}t_i R_{iJ})/(R_J TD))*(100/J) \quad (3)$$

(discrete resource-time function)

$$RU = (1/R_{max}\ TD)\int_{t\in T_D} R_{iJ}(t)dt \quad (4)$$

(Continuos resource-time function)

$$SE = 1 - (Ts - To)/To \quad (5)$$

Where:

RU : resource utilization.
t_i : expected duration of activity i.
R_{iJ} : units of resource type j of activity i.
TD : project duration.
R_J : maximum available of resource type j.
J : number of resource types.
SE : resource constrained scheduling Efficiency.
To : CPM project duration.
Ts : extended duration of the project under resource constrained situation.

In the procedure of constrained resource level, the smoothing Burgess algorithm [24] which is developed by the principal author [12], is used in the current work to determine the resource availability limit under which the scheduling process of a project network will be in constrained phase. Under the smoothed resource level, the increase of resource level increases the scheduling efficiency and decrease the resource utilization and vise is versa. This means that both RU and SE are two conflict measures depending on the resource availability level. This is why it is essential for he/or she as a decision maker or project manager to optimize the level of the constrained resource. On this basic concept, the resource availability is ranged between the minimum resource level required to start the project and the maximum resource level (smoothed) required for CP and hence, the optimum constrained resource level is determined. This optimum constrained level provides the maximum value of ARUSE. In the current study some other performance measures are used to evaluate the proposed heuristics in addition to the proposed measure. These measures are project delay (PRD), project duration (PD), iteration number (IN), weighted total delay (WTD), total resource usage time (TRUT), total resource idle time (TRIT), resource utilization (RU), resource constrained scheduling efficiency (SE), and average resource utilization and scheduling efficiency (ARUSE) [2,25].

PROPOSED HEURISTICS AND ALGORITHM FOR SCHEDULING

Different priority rules for ranking activities within scheduling procedures have been proposed for single constraint scheduling. The most common and popular heuristic techniques which have been developed by a number of researchers are listed in Table 2. All of these priority rules are an explicit function of time and resource required by an activity and all activities that succeed it. Since the rules consider the succeeding activities, it can be claimed that these priority rules implicitly consider the location of an activity on the network [25]. However, in the current work four new decision rules are developed as heuristics for scheduling single constrained resource problem. These proposed heuristics are:

Time Over Resource (TOR)

The TOR value of an activity is determined by the maximum sum of time over resource ratios that an activity controls through the network on any one path.

$$TOR(m,n) = \max_k \sum_{I,J\in CP_{mnk}} T_{IJ}/R_{IJ} \quad (6)$$

Sum of Time and Resource (SOTAR)

The SOTAR value of an activity is calculated as the maximum sum of time and resource that an activity controls through the network on any one path.

$$SOTAR(m,n) = \max_k \sum_{I,J\in CP_{mnk}} (T_{IJ}+R_{IJ}) \quad (7)$$

Table 2 Some existing priority rules for single-constraint resource scheduling.

ACTIM (m,n) = $\max_k \sum_{IJ \in CPmnk} T_{iJ}$
ACTRES (m,n) = $\max_k \sum_{IJ \in CPmnk} T_{iJ} R_{iJ}$
GENERS (m,n/w) = W[(ACTRES(m,n)/Z2)+(ACTRES(m.n)/Z1)]
TIMERS(m,n) = 0.5[(ACTIM(m,n)/Z2)+(ACTRES(m,n)/Z1)]
ROT(m,n) = $\max_k \sum_{IJ \in CP_{mnk}} R_{IJ} / T_{IJ}$
ROT-ACTRES(m,n/w) = W[(ROT(m,n)/Z3)]+(1-W) [ACTRES(m,n)/Z1]
ROT-ACTIM(m,n/w) = W[(ROT(m,n)/Z3)] + (1-W)[ACTIM(m,n)/Z2]
ACROS = $\max_k \sum_{IJ \in CP_{mnk}} R_{iJ}$
TIMROS(m.n) = W[(ACROS(m,n)/Z3]+(1-W) [ACTIM(m,n)/Z2]
TIMGEN(m,n/w)=W1[ACROS(m,n)/Z4]+W2[ACTIM(m,n)/Z2] +W3[ACTIM(m,n)/Z1], W1+W2+W3=1
SEARCH 1- $(T_I + \sum_{J \in NF_I} T_J)/(R_I + \sum_{J \in NF_I} R_J) \quad \forall i$ 2- $\sum_{J \in NF_I} T_J \quad \forall i$ 3- $(T_i + \sum_{J \in NF_I} T_J) - \sum_{J \in P_i} T_J \quad \forall i$ 4- $(T_i + \sum_{J \in NF_I} T_J) \quad \forall i$ 5- $(T_i + \sum_{J \in NF_I} T_J) / \sum_{J \in IF_I} T_J \quad \forall i$ 6- $(\sum_{J \in IFI} T_J / \sum_{J \in NFI} R_J)/(R_I / T_I) \quad \forall i$ 7- $R_I \quad \forall i$ 8- $T_I / R_I \quad \forall i$

N is the set of nodes in the directed network; $R_{i,j}$ is the resource required by the activity $T_{i,j}$ to be completed; t_{ij} is the time required by activity ij to be completed; CP_{mnk} is the set of activities of the kth directed path from node m to the last node of the network including activity mn; w=a weighting factor, $(0 \le w \le 1)$; Z1 is max (ACTRES(m,n)); Z2 is max (ACTIM(m,n)); Z3 is max (ROT(m,n)); Z4 is max (ACROS(m,n)) for all m,n $\in N$ and m < n; T_I is the time required to complete activity I; R_i is the resource required to complete activity I; IF_I is the set of activities that immediately follow activity I ; NF_i is set of activities that follow activity i; P_i is set of activities that precede activity i , i or j is activity index.

Weighted Critical Activities (WCA)

This criterion is estimated at a specific weight for critical activities (HL=2 for critical activities and HL=1 other wise), to ensure that the critical activities will scheduled at first. The WCA value is calculated as the maximum sum of time over resource ratios that an activity controls through the network on any one path multiplied by HL as a weighted factor.

$$WCA(m,n) = \max_{k} \sum_{I,J \in CP_{mnk}} HL_{IJ} * T_{IJ} / R_{IJ} \quad (8)$$

Weighted Ratio of Resource (WROR)

This criterion is evaluated at a specific weight for the ratio of resource requirement over the resource available ($R_{i,j}/RA$). The WROR value is determined as the maximum sum of time and resource multiplied by the ratio of resource requirement over the available resource.

$$WROR(m,n) = \max_{k} \sum_{I,J \in CP_{mnk}} (T_{IJ} + R_{IJ}) * R_{IJ} / RA \quad (9)$$

Also eleven heuristics as a combination between the new proposed heuristics and the common heuristics are proposed and tested in addition to the proposed heuristic rules. However, these proposed heuristics are visualized in Table 3.

Table 3 Proposed combinations of heuristics.

Rule no.	Equation of rule
Rule 1	w [TOR(m,n)]+(1-w)[ACTIM(m,n)]
Rule 2	w [TOR(m,n)]+(1-w)[ACTRES(m,n)]
Rule 3	w [TOR(m,n)]+(1-w)[ACROS(m,n)]
Rule 4	w [TOR(m,n)]+(1-w)[ROT(m,n)]
Rule 5	w [SOTAR(m,n)]+(1-w)[ACTIM(m,n)]
Rule 6	w[SOTAR(m,n)]+(1-w)[ACTRES(m,n)]
Rule 7	w [SOTAR(m,n)]+(1-w)[ACROS(m,n)]
Rule 8	w [SOTAR(m,n)]+(1-w)[ROT(m,n)]
Rule 9	w [SOTAR(m,n)]+(1-w)[TOR(m,n)]
Rule 10	w [SOTAR(m,n)]+(1-w)[WROR(m,n)]
Rule 11	w [TOR(m,n)]+(1-w)[WROR(m,n)]

For solving the tackled single constrained resource problem, the following assumptions are considered:

1. Activities duration times, and resource requirements are deterministic.
2. The minimum resource requirement to start a project is the maximum amount required by any activity of the project activity set.
3. Only one resource type is required for each project.
4. The constraint availability of resource level is deterministic. This level is less than maximum peak obtained by the smoothing process.
5. The resource requirement is unchanged over activity duration.
6. No pre-emptying is allowed.
7. However, the proposed procedure steps are as follows:

Step 1: Determine the traditional project critical path and its main characteristics $(ES_{IJ}, LS_{IJ}, TF_{IJ}, R_{IJ})$.

Step 2: The maximum peak is determined by smoothing procedure.

Step 3:Determine the optimum constrained resource level between the maximum smoothed value and the minimum resource required to start the project.

Step 4: Determine the project measures (maximum peak at earliest start and latest start, complexity measure developed in the current study, number of critical activities and paths).

Step 5: Determine the indices of all criteria under consideration for project activities. In this aspects, the considered criteria are those presented in Table 2. and rule 2 and rule 7 of SEARCH in addition to both the proposed heuristics and combinations.

Step 6: Determine the normalized indices of all criteria under consideration.

Step 7: Sort the project activities in a decreasing order according to the normalized index value.

Step 8: The decision rules applied as tie breakers are longest duration, maximum resource requirement, and random.

Step 9: Schedule the project activities using the considered heuristics and the following scheduling steps:

1. Set the starting schedule time TNOW =0, resource available R_a = optimum constrained resource level, and iteration number IN=0.
2. Determine the candidate list of activities that could start at TNOW.
3. Select the unscheduled activity(ij) with the highest normalized index.
4. If the available resource R_a is greater than or equal to the required resource by the activity ($R_{I,J}$) then go to step 6.
5. Go to step 9.
6. Schedule activity (ij).
7. Calculate the starting and completion times for that activity.
8. Determine the remainder available resource now $R_{re} = R_a - R_{ij}$.
9. In case of it is last candidate go to step 12.
10. Select the activity with the next highest priority.
11. Go to step 4.
12. In case of all the project activities are scheduled then go to step 17.
13. TNOW becomes the next minimum (TC_{IJ}).
14. Available resource at TNOW equals to the sum of the remaining resources from the preceding iteration, and the number of resources freed due to the activity completion at the previous TNOW, $R_a = R_{re} + R_{IJ}$.
15. IN=IN+1 .
16. Go to step 2 .
17. Calculate the measuring performance criteria, (PD, IN, PRD, RU%, SE%, ARUSE%, WTD, TRUT, TRIT).
18. In case of the last criterion go to step 21.
19. Select the next criterion.
20. Go to step 1.
21. Select the best criterion with the minimum completion time and stop.

Figure 1 exhibits the above algorithm steps which is transferred into a computer program for the evaluation of all criteria under consideration.

CASE STUDY

As a case study, the above procedure is applied on 50 project networks most of them have been used as investigated projects in [2,,12,26,27,28]. The other projects have been chosen randomly to increase the set of investigated projects. Table 4 lists the main characteristics of these projects.

Applying both the common and proposed scheduling criteria (26) on the considered 50 projects, the performance evaluation of the considered heuristics can be applied. Table 5 lists the output results obtained by the designed and constructed program of the proposed algorithm for project number 42. The same output results have been obtained for all projects under consideration.

RESULTS, DISCUSSION AND ANALYSIS

In order to evaluate the rules under consideration, the projects under investigation are classified into six class intervals according to their range of complexity. These class intervals are 5-15, 15-25, 25-35, 35-45, 45-55, and greater than 55. The completion dates with the minimum value as well as the rule that provides this minimum are determined for all the projects under investigation. The summation of critical paths, completion times/ each heuristic rule, the difference between them for all the considered projects, and the ranking of these heuristics based on their performance are evaluated. Figure 2 presents the variation of completion times of projects per each heuristic and their corresponding ranking positions. Based on this analysis, rule 20 will perform the best for all the investigated projects. Figure 3 exhibits a bar chart for projects yielding shortest completion time per each rule. Based on this bar chart, rules 16, 19, and 20 perform the best for the investigated projects.

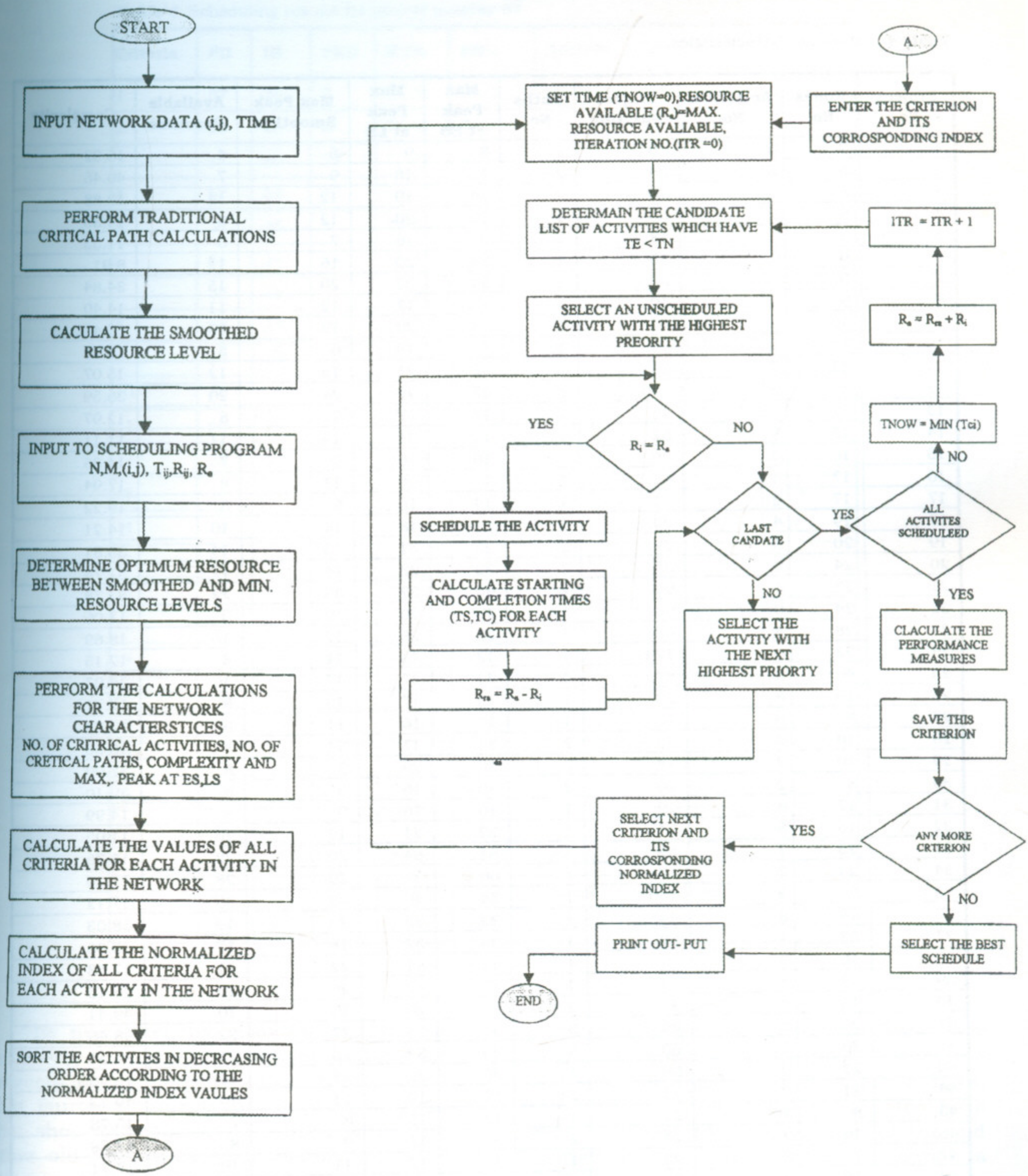

Figure 1 Computer program flow chart

Table 4 Projects characteristics.

Project No.	Nodes No.	Activities No.	Project Duration	Paths No.	Max Peak at ES	Max Peak at LS	Max Peak Smoothed	Available Resource	Complexity
1	7	0	10	1	8	9	5	4	16.92
2	8	3	24	2	12	18	9	7	40.46
3	8	3	36	1	24	19	12	11	12.88
4	9	2	30	1	15	20	12	6	14.33
5	9	1	18	1	9	16	7	5	11.53
6	9	1	15	1	23	20	16	12	8.91
7	9	5	30	2	30	32	20	15	34.84
8	9	1	10	1	16	17	12	11	14.40
9	10	2	41	1	13	20	13	10	15.47
10	10	5	29	1	7	18	6	5	13.79
11	11	3	21	1	22	21	15	12	15.07
12	11	5	100	2	27	27	21	20	36.59
13	12	5	16	1	14	17	9	8	12.97
14	15	8	52	1	19	21	14	11	11.11
15	16	4	39	1	16	16	9	7	14.36
16	17	1	61	1	18	20	11	8	17.94
17	17	2	31	1	14	16	8	6	19.22
18	19	4	35	1	11	18	11	10	14.21
19	20	8	29	2	26	31	15	14	36.81
20	24	1	35	2	32	23	14	12	51.74
21	23	1	91	2	40	32	30	22	53.78
22	24	0	63	1	16	20	10	9	13.06
23	28	8	63	1	28	28	17	15	18.69
24	32	3	124	1	12	13	11	8	12.15
25	40	4	47	1	41	37	17	16	24.07
26	10	8	23	1	15	17	13	8	17.71
27	8	0	13	1	11	16	11	6	12.74
28	10	3	25	2	14	17	11	8	40.56
29	10	2	18	2	10	20	9	8	37.00
30	8	2	20	2	10	16	9	8	39.10
31	17	8	29	1	10	16	9	8	14.99
32	15	8	34	1	32	21	19	16	11.05
33	25	7	52	1	61	64	30	28	16.76
34	24	2	57	1	60	59	29	28	17.10
35	36	2	120	1	54	46	39	36	17.12
36	18	8	44	2	32	32	25	19	58.03
37	23	4	50	1	38	32	18	17	28.86
38	16	3	16	1	41	41	22	21	17.53
39	37	5	92	1	73	67	20	19	26.15
40	16	4	27	2	32	20	16	10	49.41
41	26	6	80	3	37	34	27	22	98.46
42	30	6	50	3	35	33	25	21	84.53
43	22	0	66	1	26	27	17	12	15.26
44	11	3	15	2	12	19	11	10	49.13
45	8	1	21	1	12	16	8	7	15.78
46	10	2	24	2	9	17	9	8	43.58
47	15	8	28	1	17	17	11	10	17.71
48	18	4	41	1	10	17	7	6	8.13
49	13	7	36	1	9	10	8	7	13.86
50	22	1	47	1	16	17	10	9	14.14

Table 5 Scheduling results for project number 42.

Criteria	PD	IN	PRD	RU%	SE%	ARUSE	WTD	TRUT	TRIT
1	57	26	7	75.36	86.00	80.68	147	902	295
2	58	28	8	74.06	84.00	79.03	168	902	316
3	77	30	27	55.78	46.00	50.89	567	902	715
4	67	32	17	64.11	66.00	65.05	357	902	505
5	54	26	4	79.54	92.00	85.77	84	902	232
6	61	29	11	70.41	78.00	74.21	231	902	379
7	57	28	7	75.36	86.00	80.68	147	902	295
8	59	28	9	72.80	82.00	77.40	189	902	337
9	55	29	5	78.10	90.00	84.05	105	902	253
10	79	30	29	54.37	42.00	48.19	609	902	757
11	60	26	10	71.59	80.00	75.79	210	902	358
12	58	30	8	74.06	84.00	79.03	168	902	316
13	56	31	6	76.70	88.00	82.35	126	902	274
14	58	29	8	74.06	84.00	79.03	168	902	316
15	61	28	11	70.41	78.00	74.21	231	902	379
16	58	28	8	74.06	84.00	79.03	168	902	316
17	57	28	7	75.36	86.00	80.68	147	902	295
18	59	29	9	72.80	82.00	77.40	189	902	337
19	58	28	8	74.06	84.00	79.03	168	902	316
20	54	28	4	79.54	92.00	85.77	84	902	232
21	58	27	8	74.06	84.00	79.03	168	902	316
22	58	30	8	74.06	84.00	79.03	168	902	316
23	58	30	8	74.06	84.00	79.03	168	902	316
24	55	28	5	78.10	90.00	84.05	105	902	253
25	57	28	7	75.36	86.00	80.68	147	902	295
26	55	26	5	78.10	90.00	84.05	105	902	253

The new heuristics are investigated for achieving the shortest completion dates for projects under consideration. It was found that fourteen projects of all projects yield the shortest completion dates while the other old heuristics yield completion dates far from the shortest dates. This means that 28% of the considered projects yield shortest completion dates by only new heuristics. For the remainder projects, the new heuristics yield also the shortest dates, but these shortest completion dates have been achieved by at least one of the old heuristics. However, this remark is exhibited in Table 6.

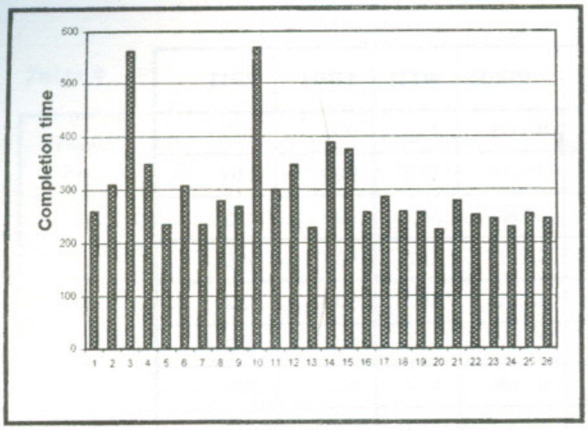

Figure 2 Variation of completion times of projects per each heuristic.

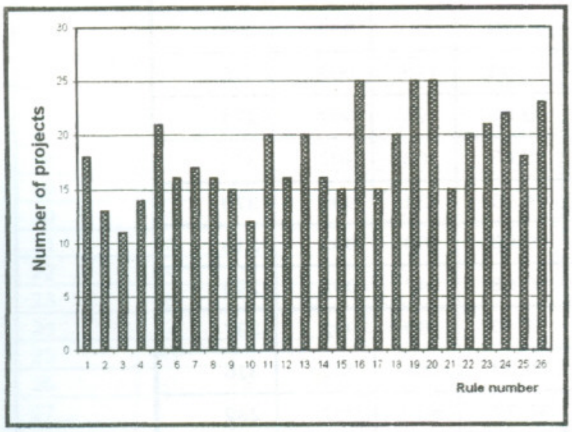

Figure 3 Histogram chart for projects yielding shortest completion time per each rule.

Table 6 Projects yielding the minimum duration using new heuristics.

Project Number	Minimum duration	Rule(s) number
1	14	18
3	39	23
14	59	16,18,19
15	43	19
16	66	15,22,25
21	102	22,23
23	69	26
25	49	13
33	54	20
34	59	26
37	53	19,26
39	93	26
40	31	13
41	85	25

Figure 4 presents the sum of rule efficiency ratios ϕ_m per each heuristic for all the investigated projects . It is obvious that heuristic rule 20 is the one with maximum efficiency ratio ρ_{mn}. The sum S_{mn} of the deviations from the minimum project durations for each project for all heuristics has been charted in Figure 5. It is noticed that rule 20 is the one with minimum project duration. The considered measuring performance criteria used in the current study have been evaluated for both old and new rules . This evaluation is presented in Figure 6. It is observed that the new heuristics will provide better performance than old rules. In order to determine which rule will perform the best with respect to project complexity, the average deviations from the observed minimum project duration and rule efficiency rations for all the considered rules for each considered class interval have been evaluated and pointed out in Table 7. Figure 7 to Figure 18 exhibit this evaluation.

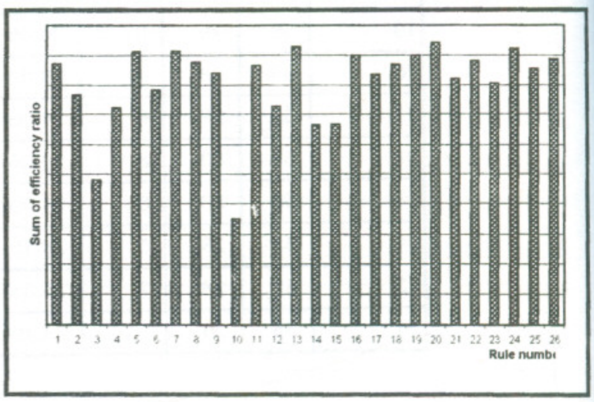

Figure 4 The sum of rule efficiency ratio for all projects of each heuristic.

Table 7 Average deviation and efficiency ratios for class intervals.

Class interval	Average deviation from minimum duration		Average efficiency ratio	
	Minimum	Best rule	Maximum	Best rule
5 – 15	2.77	20,13,11	0.975	20,13,11
15 - 25	4.33	20,26,24,19,16	0.959	16,19,26,20,24
25 - 35	2.97	17	0.972	17
35 - 45	0.5	5,20,24,26	0.995	5,20,22,23,24,26
45 - 55	4.51	22,23,13	0.958	13,22,23
> 55	1.87	25,20,13,24	0.982	25,20,13,24

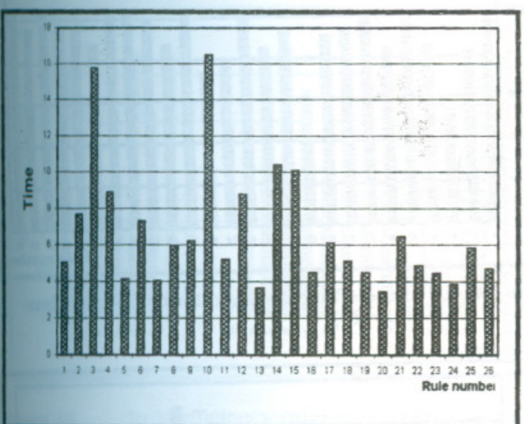

Figure 5 Deviation from the observed minimum project Time.

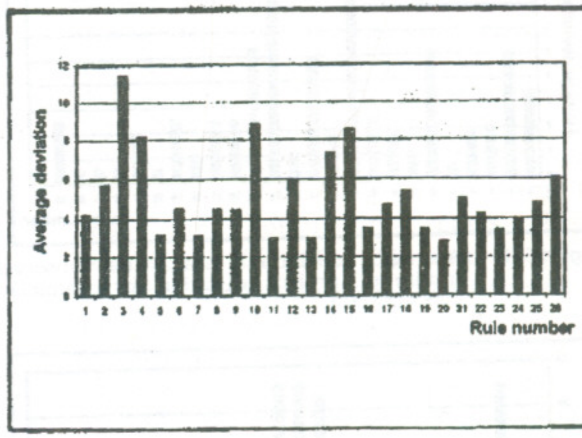

Figure 7 Average deviation from the observed minimum project duration for complexity class (5-15).

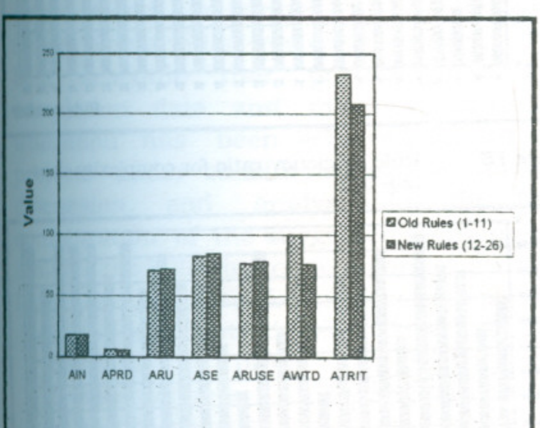

Figure 6 Average measures of performance criteria.

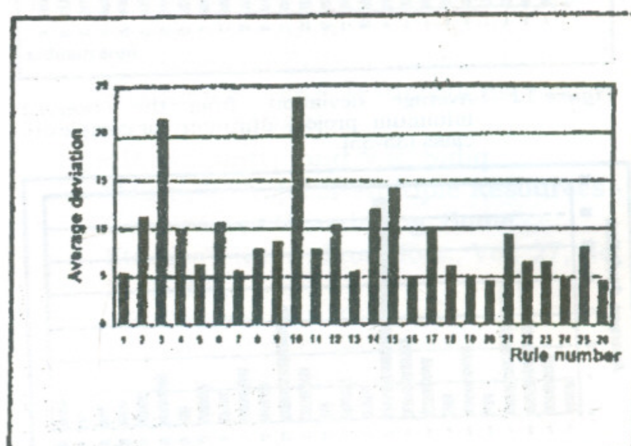

Figure 8 Average deviation from the observed minimum project duration for complexity class (15-25).

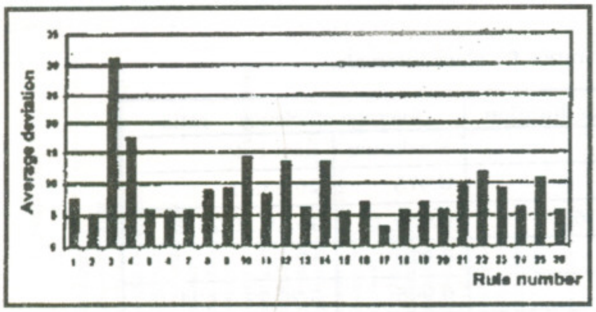

Figure 9 Average deviation from the observed minimum project duration for complexity class (25-35).

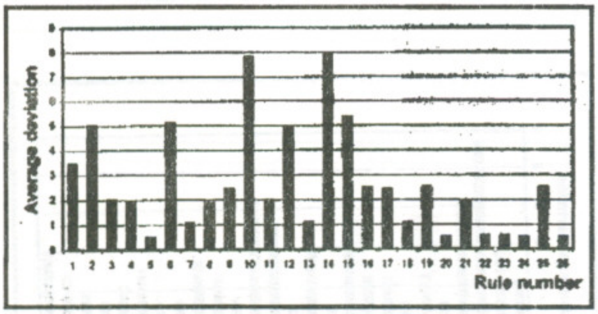

Figure 10 Average deviation from the observed minimum project duration for complexity class (35-45).

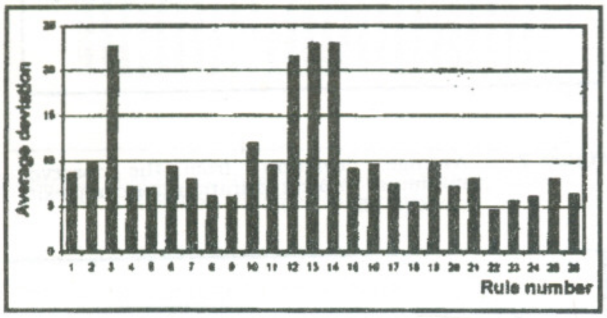

Figure 11 Average deviation from the observed minimum project duration for complexity class (35-55).

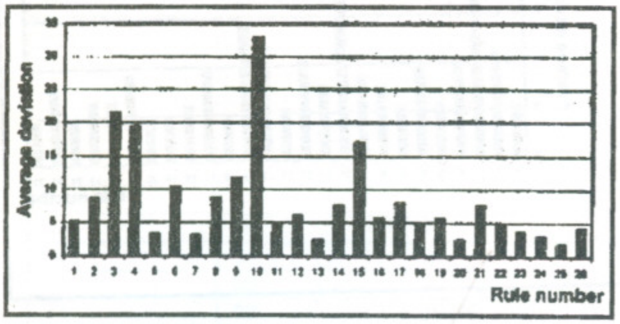

Figure 12 Average deviation from the observed minimum project duration for complexity class (>55).

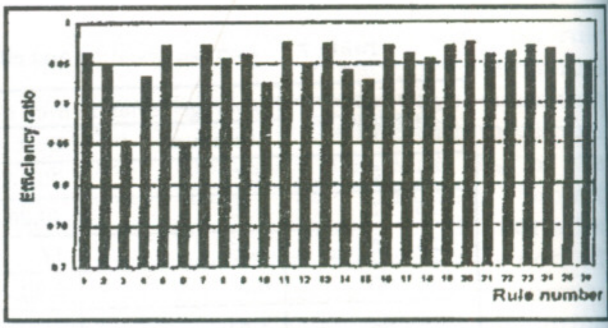

Figure 13 Rule efficiency ratio for complexity class (5-15).

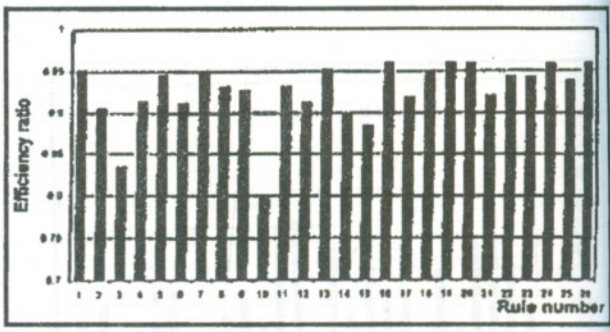

Figure 14 Rule efficiency ratio for complexity class (15- 25).

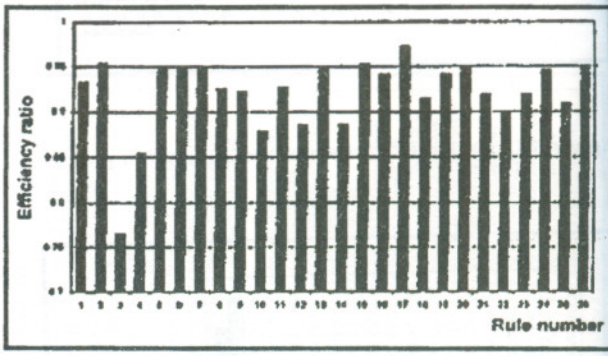

Figure 15 Rule efficiency ratio for complexity class (25- 35).

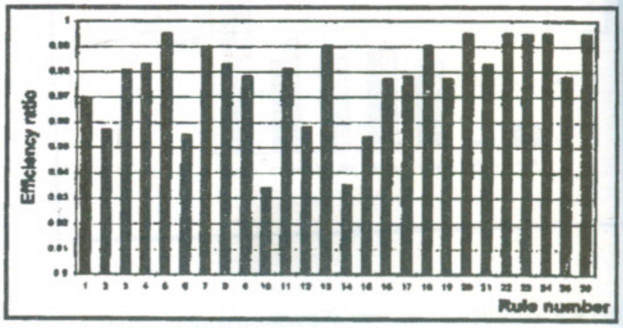

Figure 16 Rule efficiency ratio for complexity class (35- 45).

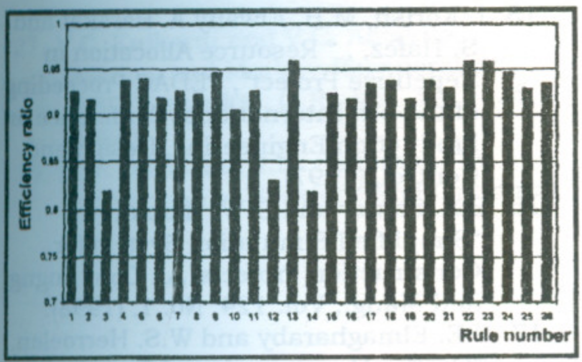

Figure 17 Rule efficiency ratio for complexity class (15- 25).

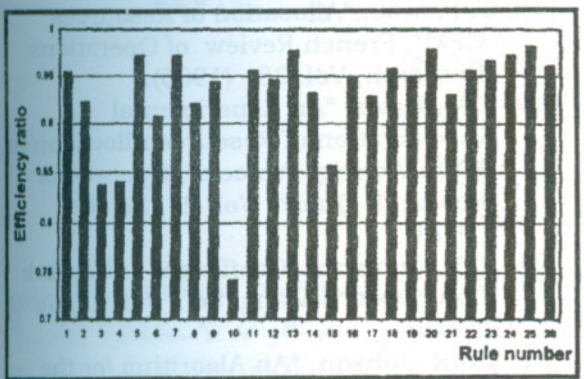

Figure 18 Rule efficiency ratio for complexity class (> 55).

CONCLUSION

The research reported in the current work demonstrated a strategy for scheduling single constrained resource problem. The best schedule that provides minimum completion date and maximum resource utilization has been achieved for all the projects under consideration. The results, discussion, and analysis for the final configuration of the suggested methodology indicate the following conclusions:

1. A new measure for project complexity has been introduced. This measure includes all project parameters and provides more sensitivity in evaluation of project complexity.
2. A new measure for scheduling performance has been developed. This measure is used to determine the optimum constraint resource level for scheduling process. This measure is recommended for the decision maker to increase or decrease his or her execution available resource level to achieve the best schedule.
3. Four new heuristics in addition to eleven combinations have been advised. The advised heuristics provide better achievements for all measuring performance criteria under consideration allover the whole projects where the new heuristics achieved alone the best schedule for 28% of projects under consideration.
4. More promising achievements have been gained for the new heuristics with respect to projects complexity classes. In this aspect, heuristics(11, 13, and 20) will perform the best for complexity class 5-15, heuristics (16,19,20, 24, and 26) will perform the best for complexity class 15-25, heuristic (17) will perform the best for complexity class 25-35, heuristics (5, 20, 24, and 26) will perform the best for complexity class 35-45, heuristics (11,22, and 23) will perform the best for complexity class 45-55, and heuristics (13, 20, 24, and 25) will perform the best for complexity class greater than 55.

REFERENCES

1. A.B. Badiru, "Towards the Standardization of Performance Measures for Project Scheduling Heuristics", IEEE Transactions, Vol. 35, No. 2, (1988).
2. R.P. Mohantly and N.R. Sidiq, "Multiple Projects-Multiple Resources - Constrained Scheduling: Some Studies", Int. J. Prod. Res., Vol. 27, No. 2, (1989).
3. R.F. Deckro, E.P. Winkofsky, J.E. Hebert and R. Gagnon, "A decomposition Approach to Multi-Project Scheduling", EJOR, Vol. 1, No. 51, (1991).
4. Q.C. Nguyen and R.E. Stone, "A multi period Mini-Max Resource Allocation Problem with Substitutable

Resources", Mang. Sci., Vol. 39, No. 8. , (1993).
5. Lee, Yong-II, Gatton and M. Thomas, "Construction Scheduling Based on Resource Constrained", Transaction of the American Association of Cost Engineers, (1994).
6. M.S. Ouli, A. El-Mohamedi and Z. Binder, " Multi-level for Resource Assignment Modeling into Project Management", Proceeding Modeling of IEEE/IAS International Conference on Industrial Automation Control, Piscataway, NJ, 95Th8005, (1995).
7. W. Chan, D.K.H. Chua and G. Kannan, "Construction Resource Scheduling with Genetic Algorithm", J. Con. Engng. and Mang., Vol. 122, No. 4. (1996).
8. L. Lorterapong and O. Moselhi, "Project-Network Analysis Using Fuzzy Sets Theory", J. Con. Engng. and Mang., Vol. 122, No. 4, (1996).
9. A.F. Samules and M.J. Burder, "Construction Representative Scheduling and Cost Management", J. Con. Engng. and Mang., Vol. 122, No. 3, (1996).
10. J.B. Pocock, C.T. Hyun, L.Y. Liu and M.K. Kim, " Relationship Between Project Interaction and Performance Indicators", J. Con. Engng. and Mang., Vol. 122, No. 2, (1996).
11. J.S. Russel, E.J. Jaselkis and S.P. Lawrence, " Continuous Assessment of Project Performance", J. Con. Engng. and Mang., Vol. 123, No. 1, (1997).
12. M.A. Shouman, "A new Approach to Schedule Projects of Single Constrained Resource Allocation", AEJ, Vol. 35, No. 4, (1997).
13. S.M. Abourizk and R.J. Wales, "Combined Discrete - Event /Continuos Simulation for Project Planning" J. Con. Engng. and Mang., Vol. 123, No. 4, (1997).
14. D.L. Erik and H.S. Willy, "A branch and Bound Procedure for the Generalized Resource Constrained Project Scheduling Problem", O.R., Vol. 45, No. 2, (1997).
15. I. Korish, M.H. Elwany A. Barakat and S. Hafez, , " Resource Allocation in Repetitive Project", PEDAC Proceeding of the 6th International Conference on Production Engineering, Design and Control, (1997).
16. B.A. Senior and D.W. Halpin, "Simplified Simulation System for Construction Projects", J. Con. Engng. and Mang., Vol. 124, No. 1, (1998).
17. S.E. Elmagharaby and W.S. Herroelen, "On the Measurement of Complexity in Activity Networks" , EJOR, Vol. 5, No. 1, (1980).
18. T. Pascoe, "Allocation of Resources CPM", French Review of Operations Research, Vol. 38, (1966).
19. E.M. Davis, "An Experimental Investigation of Resource Allocation in Multi-Activity Projects", Operations Research Quart., Vol. 24, No. 4, (1974).
20. R.A. Kaimann, "Coefficient of Network Complexity", Mang. Sci., Vol. 21, No. 2, (1974).
21. T.J.R. Johson, "An Algorithm for the Resource Constrained Project Scheduling Problem", Mang. Sci., Vol. 22, No. 11, (1976).
22. J.H. Patterson, "Project Scheduling :the Effect of Problems Structure on Heuristic Performance", Noval Res. Logistics, Vol. 23, No. 1, (1976).
23. R.J. Willis, "Critical Path Analysis and Resource Constrained Project Scheduling: Theory and Practice",EJOR, Vol. 21, No. 1, (1985).
24. A.R. Burgess, "Variation in Activity Level on A cyclical Arrow Diagram", Ind. Engng., Vol. 13, No. 2, (1962).
25. M.M. Khattab and F. Choobineh, "A New Approach for Project Scheduling with A limited Resource", Int. J. Prod. Res., Vol. 29, No. 1, (1991).
26. A.A. Ilumoka, " A tolerance Analysis Approach to Network Scheduling for Engineering Project Management", Int. J.Prod. Res., Vol. 24, No. 4, (1987).

27. V.C. Kulkarni and V.C. Adlakha, "Markov and Markov-Regenerative PERT Networks", O.R., Vol. 34, No. 5, (1986).
28. E.W. Davis and J.H. Patterson, "A comparison of Heuristic and Optimum Solution in Resource-Constrained Project Scheduling", Mang. Sci., Vol. 21, No. 8, (1975).

Received November 25, 1998
Accepted March 20, 1999

قواعد استكشافية جديدة لجدولة المشروعات ذات المورد الواحد المحدود

محمد شومان*، عبده خفاجه**، محمد زغلول**، عامر بو شعاله***

* قسم الهندسة الصناعية - جامعة الزقازيق

** قسم هندسة الانتاج - جامعة قناة السويس

*** قسم الهندسة الصناعية - جامعة قاريونس

ملخص البحث

أن نجاح القواعد الا ستكشافية المستخدمة لجدولة المشروعات يعتمد على حجم المشروع ، درجة تعقيد المشروع ، زمن تنفيذ المشروع ، متطلبات مالك المشروع ، ...... الخ. فى هذا البحث تم دراسة واستعراض لمعظم القواعد الاستكشافية العامة والأكثر شيوعا فى جدولة المشروعات ذات المورد الواحد المحدود. ايضا تم استحداث مجموعة من القواعد الاستكشافية الجديدة لجدولة المشروعات ذات المورد الواحد المحدود وقد تم ربط هذه القواعد بدرجة تعقيد المشروعات وذلك عن طريق معامل قياس درجة تعقيد المشروعات و الذى تم اقتراحه أيضا فى هذه الدراسة. أيضا تم اقتراح معامل لقياس مستوى أداء القواعد الاستكشافية فى الجدولة ولقد أظهرت الدراسة التى تمت على عدد خمسون مشروعا مختلفا فى درجات التعقيد (حتى ١٠٠) أن القواعد الجديدة المقترحة لها نتائج أفضل من القواعد المعروفة لجدولة المشروعات كما تم تحديد القواعد التى تعطى أفضل النتائج لكل فترة من فترات درجات التعقيد.