A new pragmatic appraisal criteria for the assessment of heuristic projects scheduling procedures

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Considerable progress has been made in developing heuristic-based solution procedures for scheduling projects with constrained resources. The heuristic decision rules used for project scheduling vary with the project's size, complexity, duration, personnel, and owner requirements. No simple heuristic decision criterion can be applied and perform well for different project network topologies, complexities, characteristics, and resource levels; where the project configurations play a very important and vital role in the application success of a certain specified heuristic decision criterion in scheduling. The current work presents and evaluates the most popular and active measuring performance criteria used in heuristic-based procedures (rules). Network characteristics, complexity measures, and performance measures are of concern. As an outcome of this investigation, two additional practical measuring performance criteria are developed and evaluated for scheduling project networks. Results were compared with some other measuring criteria and showed significant compatibility and practicality.

هذا البحث يقوم باستعراض لبعض واهم المعايير الفاعلة والمستخدمة في جدولة المشروعات وكذلك لمقاييس تحديد درجة صعوبة المشروعات في كل من حالتي الجدولة ذات الموارد المحدودة والموارد الغير محدودة. تم تصنيف هذه المعايير طبقا لامكانية استخدامها في الموارد المحدودة والموارد الغير محدودة وكلاهما معا. ايضا فانه تم اقتراح معيار جديد لكل من مقياس مستوى أداء الجدولة و مقياس درجة صعوبة المشروع وقد تم مقارنة المعايير المقترحة مع المعايير التقليدية وقد أعطت نتائج متوافقة مع مثيلاتها من المعايير التقليدية مما يدل على فاعليتها وكفاءة استخدامها.

Keywords: Measuring criteria, Performance measurement, Project scheduling

1. Introduction

1.1. Background

In modern management, organizations are open and complex systems interacting with the environment and pursuing objectives according to their specific mission and nature. The achievement of such objectives implies structuring the activities of the organization through projects that should be consistent with the adopted organizational objectives. Project management/and or scheduling has become such a key subject in modern organizations.

Resource allocation and project scheduling problems are generally classified by Mohantly and Siddiq [1] as, unlimited resource leveling, limited resources allocation, and long range resource planning. When an organization undertakes a project with limited resource, the management is often confronted with project completion and acquiring and maintaining an adequate level of resources. In scheduling theory renewable and nonrenewable resources are usually distinguished where the usage of renewable resources is limited for every period while nonrenewable resources are restricted to an overall consumption within the whole planning horizon.

No simple heuristic criterion has been found to perform well for wide variety of project network characteristics, and resource levels. The success of a certain specified heuristic depends mainly on the project characteristics. There is still no such procedure, which is considered to be computationally feasible for the large and complex projects that occur in practice. Research on heuristic solution procedures has been still popular because most success to date has been found in the application of heuristic techniques.

1.2. Review of literature

An evaluation of due date resource allocation, project release, and activity scheduling rules in a multi-project environment has been developed by Yang and Sum [2]. The results show that workload sensitive due date rules always provide better due date estimate than workload insensitive due date rules.

A vast literature survey with a perspective that integrates models, data, and optimal and heuristic algorithms, for the major classes of project scheduling problems has been presented by Kolisch and Padman [3]. The study includes recent surveys that have compared commercial project scheduling systems. An overview of web-based decision support systems and discuss the potential of this technology in enabling and facilitating researchers and practitioners in identifying new areas of inquiry and application. A heuristic procedure for a non preemptive resource constrained project scheduling problem in which the duration/cost of an activity is determined by the mode selection and duration crashing applied within the selected mode is introduced by Ahn and Erenguc [4]. An instance generator for resource-constrained project-scheduling problems with partially renewable resources has constructed by Drexl et al. [5]. Non-preemptive variant of a resource-constrained project-scheduling problem with mode identity in considered by Salewski et al. [6]. The problem is a substantial and nontrivial generalization of the well-known multi-mode case. An analysis of the characteristics of projects in diverse industries is presented by Tukel and Rom [7]. The study was conducted to identify and categorize characteristics of projects in various industries as well as performance measures and constraints. A variety of statistical techniques are used to describe project profiles, ranging from simple descriptive statistics to multivariate analysis. Heuristics for network project scheduling with random activity duration's depending on the resource allocation have been developed by Ginzburg and Gonik [8,9]. The objective is to minimize the expected project duration by determining for each activity its starting time and the assigned resource capacities. The resource project-scheduling model is a NP-complete knapsack resource reallocation problem. A lookover algorithm and 0-1-integer programming have been used as solver tools. The reported results are promising. Unfortunately, most of the work on project evaluation has not considered the interactive relationship among the evaluation, project topography, and characteristics, and adopted schedule, Tavares [10]. Snoke [11] developed a new heuristic. The heuristic employs the well-known activity list representation and considers two different decoding procedures. An additional gene in the representation determines which of the two decoding procedures is actually used to compute a schedule for an individual. Computational experiments show that the mechanism of self–adaptation is capable to exploit the benefits of both decoding procedures. A new approach for scheduling resource-constrained projects is presented by Sprecher [12]. The approach combines elements of heuristic and exact solution procedures. The project considered is decomposed into subprojects, the sub problems are optimally solved, and the solutions are concatenated. Several of the best-known makespans are improved. The algorithm has reduced best-known makespans than the state-of-the-art heuristic for medium-sized projects.

It has been noticed that for each suggested solution procedure, there must be either quantitative or qualitative measure to verify the effectiveness of the proposed technique as a solver tool. Due to the wide variety of characteristics for project scheduling problems, the quantitative measuring criteria of the effectiveness of the proposed techniques as solver tools will be more sensitive and hugely spread. In this work a collection of the most popular and active criteria for measuring the effectiveness of solver tools in project scheduling is presented. Two additional complexity and performance criteria are developed and its practicality and effectiveness were also evaluated.

2. Measures of network characteristics

One possible measure of network size; is the *total number of nodes* contained in the network, including the necessary single beginning and single ending nodes. Network shape can be specified on the basis of three separate factors; a measure of *network length*, a measure of *network width*, and a measure of the *relationship of length to width*.

Time-related measures such as average activity duration, variance in duration, and critical path duration are used to specify networks. Also, the total slack contained in the network and the total free slack are important measures. Strictly speaking, each of these measures is a function of network logic and might be included in the first class of measures, Davis [13]. Another measure of time, originally suggested by Pascoe [14], is termed by "network density" and is presented as shown in eq. (1):

$$\text{Network density} = \frac{\text{Sum of activities durations}}{\text{Sum of activities durations} + \text{total free slack}} \,. \quad (1)$$

For this measure, 0 < Density ≤1, for the purpose of resource scheduling it can be seen that high values of density indicate less free slack and, consequently, less freedom to make sequencing decisions without causing further resource conflicts. In a network with density = 1, all jobs are critical. Finally, the *criticality in dex CI* of a resource, as defined by Moder and Phillips [15], is a ratio of the average daily resource required to the average daily resource available. This index is shown in eq. (2):

$$\text{Criticality index} = \frac{\text{Average daily resource required}}{\text{Average daily resource available}} \,. \quad (2)$$

In general, one could expect that as the Criticality Index for a resource increases, project duration would increase.

3. Measuring criteria of project's scheduling

No single procedure is computationally feasible for the large and complex projects and the success of a certain specified heuristic depends mainly on the project characteristics. Since most success to date has been found in the application of heuristic techniques, research on heuristic solution procedures is still popular. The search for measuring criteria that verify the effectiveness of the proposed heuristic solution procedure is a must.

The measuring criteria are classified into complexity measures and performance measures. Performance measures are categorized into performance measures for constrained resource problem, performance measures for unconstrained resource problem, and performance measures for both of them. Appendix A provides an explanation of the abbreviations, variables and parameters used in the equations of this work.

3.1. Complexity

The measurement of "complexity" of activity networks is needed to estimate the computing requirements and/or to validly compare alternative heuristic procedure. There are several quantitative and qualitative factors with unknown interactions that are present in project networks. Measure of project complexity should be used as a relative measure of comparison rather than as an absolute indication of the difficulty involved in scheduling a given project. Evidently, a choice between two proposed algorithms, or the determination of the efficiency of a particular algorithm, would be greatly facilitated if there exist a measure of network complexity. This would eliminate any possible bias in the conclusions regarding the efficiency of a particular algorithm relative to others by ensuring that the algorithm is evaluated at several points in the "range of complexity".

3.1.1. Coefficient of network complexity

Pascoe [14] (eq. 3), Davis [16] (eq. 4), and Kaimann [17] (eq. 5) suggested complexity measures that rely totally on the count of the activities and nodes in the network. Since it is easy to construct networks of equal number of arcs A and nodes N_n but with varying degrees of difficulty in analysis, it is difficult to see how these measures can be discriminated among each one of them.

$$CNC(P) = \frac{A}{N_n} \,, \quad (3)$$

$$CNC(D) = 2(A - N_n + 1)/(N_n - 1)(N_n - 2)\,, \tag{4}$$

$$CNC(K) = A^2 / N_n \;. \tag{5}$$

The quantitative measure of complexity of a project network presented by Badriu [18], eq. (6), is more sensitive than the other measures. In the complexity measure, the maximum number of immediate processor P is a multiplicative factor that increases the complexity and potential for bottlenecks in a project network. The 1–(1/A) is a fraction measure (between 0 and 1) and 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 decrease, 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 overall the difference resource type j relative. Having project duration D_c 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. As it has been focused that this measure handles most of the project network parameters that affecting its complexity. This measure of complexity is more sensitive to the changes in the network data and gives accurate quantified results when comparing the complexities of networks.

$$CNC(B) = \left[\frac{P}{D_c} \left\{ \left(1 - \frac{1}{A}\right) \sum_{i=1}^{A} t_i + \sum_{j=1}^{R} \left(\sum^{A} t_i r_{ij} \Big/ RA_j \right) \right\} \right] . \tag{6}$$

When the number of critical paths in network W increases, the complexity of network will be increased. Also, as the number of critical activities in the network Ac increases the complexity of project network will be increased. The quantitative measure of complexity of project network presented by Shouman et al. [19] (eq. (7), is more sensitive than that presented by Badriu [18]. However for this measure, when Ac equals A then W equal to unity and the project will be of serial structure and the measure is the same as that suggested by Badriu's [18] measure. The main privilege of this measure is that, it considers availability characteristics as well as number of critical activities and critical paths.

$$CNC(S) = \left[\frac{W}{(1 - Ac/A)} \right] \left[\frac{P}{D_c} \left\{ \left(1 - \frac{1}{A}\right) \sum_{i=1}^{A} t_i + \sum_{j=1}^{R} \left(\sum^{A} t_i r_{ij} \Big/ RA_j \right) \right\} \right] . \tag{7}$$

3.1.2. Total activity density (T-density)

The total activity density, T-density as a coefficient of network complexity which is suggested by Johnson [20], (eq. (8)) considers only the maximum difference between the predecessor and successor activities all over the network nodes ignoring all the other network characteristics, (size, shape, duration, resources, ...etc.). The same remark can be focused for the average activity density as a coefficient of network complexity which, is developed by Patterson [21], (eq. (9)).

$$T - Density = \sum_{N} max \left\{ \begin{matrix} 0, number\ of\ predecessor\ activities - \\ number\ of\ successor\ activities \end{matrix} \right\} . \tag{8}$$

3.1.3. Average activity density

$$Average\ \ activity\ \ density = \frac{T - density}{N_n} \;. \tag{9}$$

3.2. Performance

Performance measures are absolutely essential for running of projects and achieving targeted strategies. It does not hold all performance smooth or measurement systems to be created equal. Performance measures are considered as a core of system standards, which are concern with the acceptable performance measures. Two key factors influencing the selection of the scheduling policy of the project in the execution phase. These factors are the network topology and the available resource. The most frequently used measure of performance for a resource scheduling heuristic is the project duration. Although this measure evaluates the primary objective of a project scheduling heuristic, it does not evaluate other aspects of a heuristic performance. Patterson [21] classified the measuring criteria into three categories. In the first category, time and network - based parameters are computed prior to critical path analysis. In the second category, time and network -based parameters are computed subsequent to critical path analysis. In the third category, resource-based parameters, which are generally computed subsequent to critical path analysis, are included.

The evaluation of the models should be based upon a set of effectiveness measures. In going project organization, may effectiveness measure that may directly reflect management's view point have to be translated into objective indicators for performance reporting. Mohanty and Sidik [22], Khattab and Ghoobienh [23], Shouman et al.[19], and many others suggested some measuring performance criteria to evaluate the performance of the heuristics. These measures have been classified into three groups. The first group is applicable for implementation for both constrained and unconstrained resource projects. The second is applicable for the implementation of constrained resource projects. The third is applicable for implementation of unconstrained resource projects.

3.2.1. Performance measures for constrained and unconstrained resource types

Total Project Delay (TPD): For a given set of projects, total project delay is given as the sum of the difference between the assigned scheduled finish time of a project and the length of the critical in an early start schedule. This measure gives an indication of the delays introduced as a result of limitations on resource availability and as a result of the scheduling rule employed. This can be presented in eq. (10):

$$TPD = \sum_{j=1}^{M} (T_{sj} - T_{oj}) \, . \tag{10}$$

Weighted Total Delay (WTD): For a given set of projects the weighted total delay is given as the sum of the total resources demand by a project multiplied by the total delay of the project. This measure is shown in eq. (11):

$$WTD = \sum_{j=1}^{M} \sum_{i=1}^{N} W_N R_{Nt} (T_{sj} - T_{oj}) \, . \tag{11}$$

Average Saved Resource Time (ASRT): For a given set of projects, the *ASRT* is given as the average sum of the product of the difference between maximum peaks before and after smoothing process and the length of the critical path. This relation is shown in eq. (12):

$$ASRT = \{ \sum_{J=1}^{M} \sum_{I=1}^{N} CP(R_{1ij} - R_{2ij}) \} / M \, . \tag{12}$$

Deviation From Normal Smoothing (DFNS): For a given set of projects, the *DFNS* is given as average sum of the absolute percentage of the relative ratio for the difference of maximum peak obtained when smoothing lower priority resource itself and the maximum peak obtained due to smoothing highest priority resource; to that maximum obtained when smoothing lower priority resource. This relation is shown in eq. (13):

$$DFNS= \left\{ \sum_{J}^{M} \sum_{1}^{N} ((MS_3 - MS_2)/(MS_3) * 100 \right\} / LM \, . \tag{13}$$

Total Resource-Idle Time (TRIT): This is the amount of time that resources are idle during a schedule span. Idle time can be measured in units of resource-type days, eq. (14). It is a result of the unavailability of direct project work, which in turn is a result of the schedule method employed.

$$TRIT = \sum_{i=1}^{N} \sum_{t}^{CP} W_i \, R_{it} \, t \, . \tag{14}$$

Resource Utilization (RU): Resource utilization measures how efficient the scheduler uses its resources as a function of time. It is defined as the ratio of the total time-resource demanded by a project, which is a function of priority rule employed, divided by the maximum of time-resource R_i *PC* available during the project duration as in eq. (15):

$$RU = \sum_{i=i}^{N} \left(\frac{\sum_{k=1}^{A} t_k r_{ik}}{R_i PC} \times 100 \right) \bigg/ N . \qquad (15)$$

Both project duration and resource utilization, as measures of effectiveness of a scheduling method should be used. When two or more methods are used to schedule the same project, these measures are equivalent, and the integer-valued project duration should be preferred. For comparisons between different projects the dimensionless *RU* should be used, as it is independent of work content and has better statistical properties.

Project Delay (PD): Project delay refers to the departure of a project past its CPM calculated finish time, eq. (16):

$$PD = T_s - T_0 ,\; T_s \geq T_o \text{ constrained resources.} \qquad (16)$$

If $T_s < T_o$ then unconstrained resources (crashing or compression problem).

Average Smoothing Efficiency Factor (ASEF): For a given set of projects, *ASEF* is given as the average sum of the relative ratio between saved resource time and actual smoothed resource time required for smoothing process. This criterion is presented mathematically as in eq. (17):

$$ASEF = \left\{ \sum_{J=1}^{M} \sum_{I=1}^{N} CP(R_{1ij} - R_{2ij})/R_{2ij} \right\} \bigg/ M . \qquad (17)$$

Average Criticality Efficiency Index (ACEI): For a given set of projects, *ACEI* is given as the average sum of the relative ratio between saved resource time and actual smoothed resource time required for smoothing process. This criterion is presented mathematically as in eq. (18):

$$ACEI= \left\{ \sum_{J=1}^{M} \sum_{I=1}^{N} \sum_{d=1}^{D(J)} ((R_{2ijd}/R_{2ij}) - (R_{1ijd}/R_{1ij})) \right\} \bigg/ M . \qquad (18)$$

For the above criteria, R_{1ij} may be determined at either earliest start schedule or latest start schedule for perfect evaluation of the considered criteria, R_{1ij}, must be held for all priority orders at either earliest or latest start. In case of in phase resource functions, the criteria value will be positive, while for out-of-phase functions the criteria value may be positive, zero, or negative. This is due to the smoothing process will unify the resource usage for highest priority order, i.e. for this resource order $R_{1ij} < R_{2ij}$, for dissimilar functions, R_{1ij} may be $\leq R_{2ij}$.

Smoothing Algorithm (SA): The presented development in smoothing algorithm can be considered as a scientific bases for determining the resource bounds at which the execution of projects will be considered either in constrained or unconstrained phase; where it determines the minimum-maximum peak for execution, as in eq. (19):

$$SA = Minimize \sum_{K=1}^{C} \sum_{j=1}^{L} \sum_{i=ES}^{LF} R_{ijk}^{2} . \qquad (19)$$

3.2.2. Performance measures for constrained resource type

Resource-constrained scheduling efficiency *SE* is presented in eq. (20):

$$SE = 1 - (T_s - T_o)/T_o . \qquad (20)$$

Average Resource Utilization and Scheduling Efficiency (ARUSE): The minimum resource required to execute the project is the maximum value required by any activity in the project network, as stated by Willis [24], while the resource level at which the project will be executed at a higher efficiency in a constraint phase is determined as shown in eq. (21), as stated by Shouman et al. [19]:

$$ARUSE = (RU + SE)/2 \; . \qquad (21)$$

Burgess algorithm [25] is used to determine the resource limit in the constrained phase. Under the smoothed resource level, the increase of resource level, increases the scheduling efficiency and decreases the resource utilization and vise is versa. This means that both Resource Utilization (RU) and Scheduling Efficiency (SE) are two conflict measures depending on the resource availability level. It is essential for the 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*. The optimum constrained resource level is somewhere in between. This optimum constrained level provides the maximum value of average resource utilization and scheduling efficiency.

Efficiency ratio (ρ_{mn}): To compare the heuristic scheduling rules with their performance on scheduling process on the basis of the raw project duration they yield, the following aggregate measures are proposed by Badiru [18]. The first one is an evaluation of the ratio of the minimum project duration observed to the project duration obtained under each rule. For each rule *m*, the ratio under each test problem *n* is computed as in eq. (22):

$$\rho_{mn} = \frac{q_n}{PL_{mn}} \qquad m = 1,2,....,M; n = 1,2,...N \; . \qquad (22)$$

Frequency of obtaining the Shortest Duration (ShD): This measure identifies the number of times (networks) that a heuristic provides the shortest duration relative to the other heuristics being investigate.

3.2.3. Performance measures for unconstrained resource type

Resource Range (RR): The resource range is the difference between the minimum resource level R_{min} needed to complete the project and the resource level required to schedule the activities by the critical path method R_c, eq. (23):

$$RR = (R_c - R_{min}) \; . \qquad (23)$$

This measure may have positive, negative or zero values. Negative or zero values indicates that condition is unconstrained.

4. Proposed complexity and performance measures

Based on the complexity and performance measures presented earlier in section 3, the authors developed two new practical performance and complexity measures for project's scheduling. In the following sections the two measures are presented as well as illustrative examples.

4.1. Measure of complexity

Although the degree of complexity measures, presented in section 3.1 are sensitive to evaluate the project's complexity, none of them considered the number of parallel chains or paths belong to the project as an important and efficient indicator in the evaluation of the degree of complexity. The following complexity measure is suggested (eq. (24)) which takes into consideration the number of parallel paths:

Degree of complexity measure=

$$(\sum_{i=1}^{n}\sum_{j=1}^{n} N_{pc})/(\sum_{i=1}^{n}\sum_{j=j+1}^{n}(t_{ij} * X_{ij})) \; . \qquad (24)$$

To verify the sensitivity of the developed measure two different projects (b1) and (b2) have the same number of nodes were considered. The network of the two projects is shown in Appendix B. The number of parallel chains of the projects' network is shown in table 1.

Applying eq. (24), the degree of complexity of projects (b1) and (b2) are exhibited in table 1. Although the two projects have the same number of nodes, project (b2) has higher complexity value. This is attributed to the number of parallel paths. The proposed degree of complexity measure (eq. (24)) is more sensitive to the project's number of parallel paths.

Table 1
Number of parallel chains of projects' (b1) and (b2) network

Project (b1)										Project (b2)									
N_n	1	2	3	4	5	6	7	8	9	N_n	1	2	3	4	5	6	7	8	9
1	-	0	0	0	0	0	0	3(6)	4(8)	1	-	0	2(5)	0	3(10)	4(14)	0	5(22)	9(30)
2	-	-	0	0	0	0	0	0	0	2	-	-	0	0	2(5)	3(9)	0	0	5(25)
3	-	-	-	0	0	0	0	2(3)	0	3	-	-	-	0	0	0	0	0	0
4	-	-	-	-	0	0	0	0	0	4	-	-	-	-	0	0	0	0	0
5	-	-	-	-	-	0	0	0	0	5	-	-	-	-	-	0	0	0	3(20)
6	-	-	-	-	-	-	0	0	0	6	-	-	-	-	-	-	0	0	0
7	-	-	-	-	-	-	-	0	0	7	-	-	-	-	-	-	-	0	0
8	-	-	-	-	-	-	-	-	0	8	-	-	-	-	-	-	-	-	0
9	-	-	-	-	-	-	-	-	-	9	-	-	-	-	-	-	-	-	-
Degree of complexity (b1) = 1.66										Degree of complexity (b2) = 2.59									

4.2. Performance measure

Performance measures presented in section 3.2 lacked the consideration of the utilized resources. In this aspect, two performance measures were developed namely the Sum Of Square Deviation from average workforce *SOSD* and Sum Of Absolute Deviation from average workforce *SOAD*, eqs. (25 and 26), respectively. The smaller values of *SOSD* and/or *SOAD* indicate that the resource profiles are in good smoothed modes.

$$SOSD=\left(deviation-\frac{\sum of\ resource\ \ duration}{CPM}\right)^2,(25)$$

$$SOAD=\sum\left|deviation-\frac{\sum of\ resource\ \ duration}{CPM}\right|.(26)$$

Fig. 1 represents a resource profile of a project in which ∑average workforce = 125/19 = 6.57. By applying the developed performance measures eqs. (25, 26), the following values are obtained:

SOSD = 104.633
SOAD = 34.35

These values indicate that the developed performance measure is sensitive to the workforce resource.

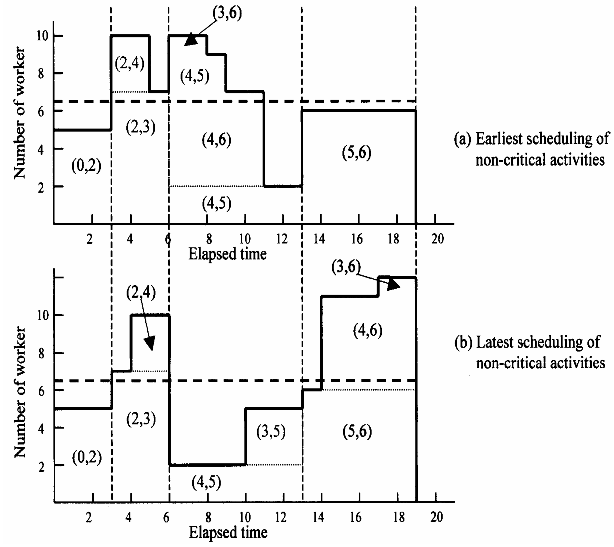


Fig. 1. Resource profile of a certain project.

5. Evaluating the proposed complexity and performance measures

The effectiveness and compatibility of the proposed measures were evaluated by considering five different projects c1, c2, c3, c4 and c5. The network arrow diagrams of these projects are illustrated in Appendix C. A comparison between the complexity and performance values determined by the proposed measures and some selected measures. Table 2 presents the basic characteristics and topologies of the five projects considered in the comparison.

5.1. Complexity measure

Degree of complexity values determined, using the proposed formula, were compared with those obtained using the selected complexity measures, (see table 3). Fig. 2 shows a plot of the complexity values of both the proposed degree of complexity measure and other measures. Fig. 2 shows that the proposed measures follow the same trend of the other measures.

5.2. Performance measure

The proposed performance values were evaluated, by SOSD and SOAD measures, against selected three performance measures (PD, WTD and TRIT). The obtained performance values of the proposed and the selected performance measures were compared (see table 4). Figs. 3-a and 3-b show a plot of performance values of the proposed and the selected measures. Fig. 3-a shows the performance values as evaluated. In order to cancel the effect of the difference in scale, normalization process is applied to the evaluated parameter and exhibited in fig. 3-b. It is clear that the proposed measures follow the same trend and the proposed complexity measure is compatible with other measures.

Table 2
Characteristics of the considered networks

Project	Number of nodes	Number of activities	Project duration	Number of paths	Max. peak at ES	Max. peak at LS	Max. peak smoothed	Available resources	MS2	ML2	MS2	MS3
c1	7	10	10	1	8	9	5	4	16	16	19	16
c2	8	13	24	2	12	18	9	7	17	18	12	12
c3	8	13	36	1	24	19	12	11	15	17	15	15
c4	9	12	30	1	15	20	12	6	8	8	8	8
c5	9	11	18	1	9	16	7	5	13	9	12	9

Table 3
Calculated complexity measures of the five considered projects

Project	Other complexity measures	Proposed complexity measure
c1	16.92	2.175
c2	40.46	4.588
c3	12.88	1.365
c4	14.33	2.523
c5	11.53	3.516

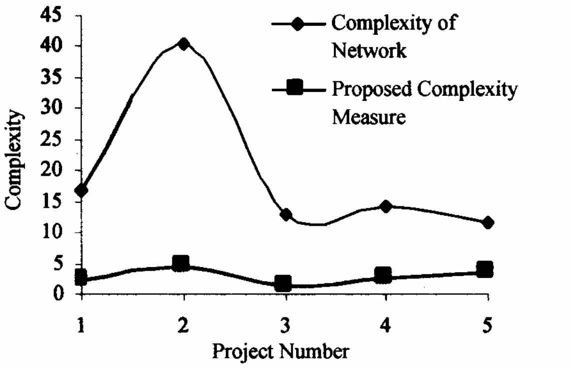


Fig. 2. Comparison of projects' complexity measures.

Table 4
Calculated performance measures of the five considered projects

Project	Project Delay (PD)	Weighted Total Delay (WTD)	Total Resource Idle Time (TRIT)	Sum Of Square deviation from Average workforce (SOSD)	Sum Of Absolute Deviation from average workforce (SOAD)
c1	15	20	11	67.6	23.6
c2	31	49	72	366	78
c3	43	77	159	1198	192
c4	40	60	42	288.7	64.6
c5	20	10	34	180	44

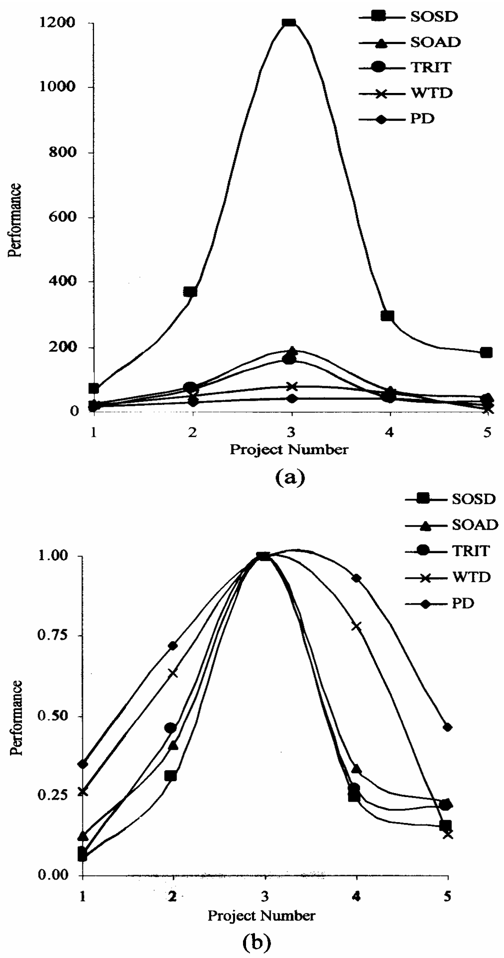


Fig. 3. Performance values of the five considered projects (a) as calculated, (b) normalized.

6. Conclusions

Classification of measuring criteria of project scheduling for constrained and unconstrained single resource problems is presented. These measures are concerned to network characteristics, degree of complexity levels, and performance measures of project scheduling procedures. The characteristics, number of critical activities, single critical path, multiple-critical paths, and the ratio between resource requirements and resource availability are of vital concern in the evaluation of all the measures under consideration. Moreover, all these key role parameters have a great core influence in the selection of scheduling criteria. Also, this paper presents new pragmatic appraisal criteria for the assessment of heuristic project scheduling procedures. The new approaches are used for evaluating the complexity and performance of project's schedules. The proposed measures were evaluated using five different hypothetical projects. The obtained results indicated that the proposed complexity and performance measures are sensitive to projects topographical variations and follow the same trends other measures do.

Appendix A

abbreviations, variables and parameters

A.1. Abbreviations

ACEI is the average criticality efficiency index,
ARUSE is the average resource utilization and scheduling efficiency,
ASEF is the average smoothing efficiency factor,
ASRT is the average saved resource time,
CI is the criticality index of a resource,
CNC is the coefficient of network complexity,
DFNS is the deviation from normal smoothing,
PD is the project delay,
RER is the rule efficiency ratio,
RR is the resource range,
SA is the smoothing algorithm,
SE is the resource-constrained scheduling efficiency,
ShD is the frequency of obtaining the shortest duration,
SOAD is the sum of absolute deviation from average workforce,
SOSD is the sum of square deviation from average workforce,
TPD is the total project delay,
TRIT is the total resource-idle time, and
WTD is the weighted total delay,

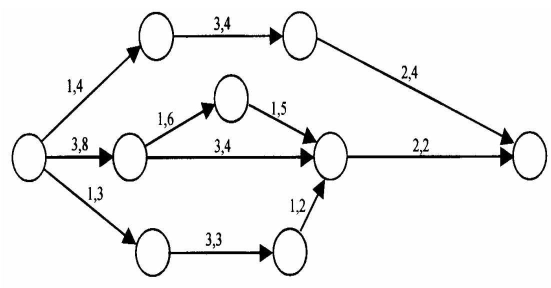
A.2. Variables and parameters

ρ_{mn} is the efficiency ratio for rule (m) under test problem (n),
A is the number of activities in the network,
Ac is the number of critical activities in the network,
C is the the number of iteration cycles which terminates at minimum two consecutive iterations,
CP is the critical path length,

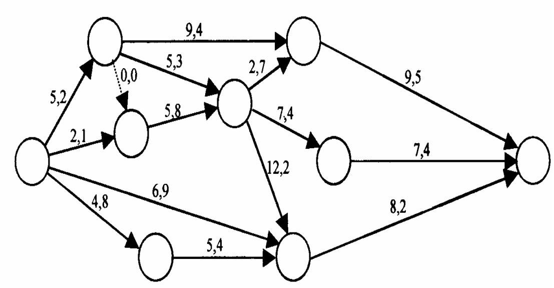
D (j) is the project duration,
D_c is the project duration with no resource constraint,
ES, LF are the earliest start and latest finish for activity j,
L is the number of non-critical activities
LM is the smoothing lower priority resource,
M is the project set,
MS2 is the maximum peak of lower priority resource due to smoothing of highest priority resource,
MS3 is the maximum peak of lower porirty resource due to smoothing lower priority resource,
N is the resource set,
N_n is the number of nodes in the network,
N_{pc} is the no. of parallel chains in the network (> 1),
P is the maximum units of immediate predecessors in the network,
PC is the project completion time,
PL_{mn} is the the project duration for test problem n under rule (m),
q_n is the minimum project duration observed for test problem,
R is the number of resource types,
R_{1ij} , R_{2ij} are the maximum peaks of resource type i before and after smoothing, respectively,
R_{1ijd},R_{2ijd} are the daily resource requirements before and after smoothing process, respectively,
RA_j is the maximum units of resource type j available,
R_c is the resource level required to schedule the activities by the CPM,
R_i is the maximum resource of type i available,
r_{ij} is the units of resource type j required by activity (i),
R_{ijk} is the resource required at duration time i,
r_{ik} is the units of resource type i required by activity k,
R_{it} is the total resources demanded by a project,
R_{min} is the minimum resource level or maximum value required by an activity in the project,
R_{Nt} is the resource required by a project,
R_u is the resource utilization,
S_E is the scheduling efficiency,
t is the activity time,
t_i is the expected duration for activity (i),
t_{ij} is the duration of activity ij,
t_k is the time of avtivity k,
T_o is the duration of the project as computed by CPM,
T_{oj} is the duration of the i^{th} project as computed by CPM,
Ts is the extended duration of the project under resource constrained situations,
T_{sj} is the extended duration of the i^{th} project under resource constrained situations,
W is the number of critical paths in network,
W_i is the weight of resource type i,
W_N is the weight of resource type N, and
X_{ij} is the integer variable (0 or 1), the integer variable equals 1 for critical activity on path ij and zero otherwise.

Appendix B

Networks of projects (b1) and (b2) time and resource are separated by a comma on each activity



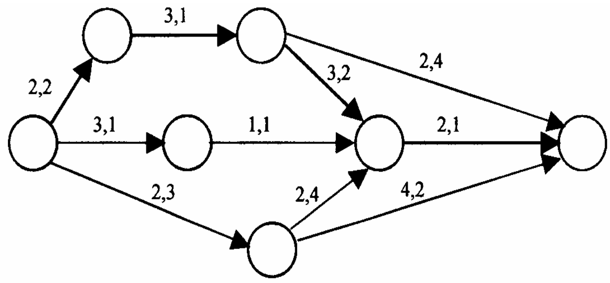
Project (b1)



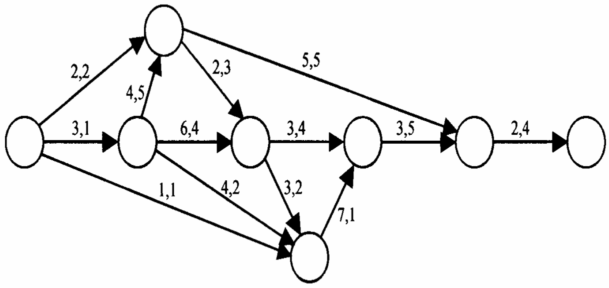
Project (b2)

Appendix C

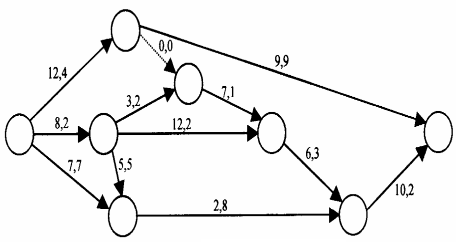
Networks of the five considered projects



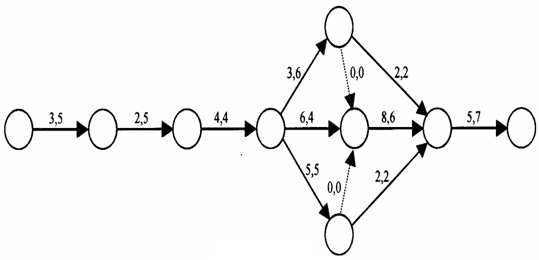
Project (c1)



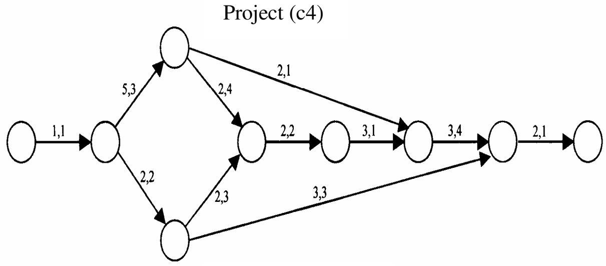
Project (c2)



Project (c3)



Project (c4)



Project (c5)

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Received May 25, 2002
Accepted December 17, 2002