A Novel Heuristic Approach for Multi-Mode Resource Constrained Project Scheduling Problems

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Abstract

Multimode project scheduling problem has significant application in project-based organizations. It is an NP-hard (Non-Polynomial) problem and, therefore, several heuristic and meta heuristic techniques are employed in literature to solve these problems. In this paper, we propose a novel heuristic approach for multimode resource constrained project scheduling (MMRCPS). The proposed heuristic introduces an efficient technique to simultaneously optimize the resource utilization and activity mode selection. The heuristic is designed for makespan minimization. Furthermore, it incorporates certain activity shifting techniques to reduce makespan of the project. The proposed heuristic is tested on benchmark instances taken from PSPLIB (Project scheduling problem library) and a comparison is performed against optimal results. The proposed heuristic delivers better results in comparison with those reported in the existing literature.

Keywords—project scheduling, multi-mode problem, NP-hard, heuristic, makespan minimization.

1 Introduction

Scheduling projects is a core area under the scope of project management. A well-organized project schedule leads to efficient management of project time, resources, cost and quality. Project scheduling approaches rely on the type and nature of the activities and the resources required for the completion of the project. In one of the scenarios, a project activity can be completed in different ways based on the number and the type of the resources required by the activity. The resources are combination of renewable and nonrenewable type of resources [1]. The duration of the activity varies for the type and number of resource available. The time required for activity completion under the designated resource type and requirements is the activity performance mode. The variations in resource type and requirements for an activity leads to different time duration for that activity. The set of time duration obtained from these variations for an activity gives the number of modes. A project scheduling problem in which each activity in the project has multiple modes is known as a multimode project scheduling problem. The resource limitations in this type of problems turn them into multi-mode, resource constrained, project scheduling problems (MMRCPSP).

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A multimode version of RCPSP has a complex nature. It is a NP-hard problem and gets more multifaceted with the increase in number of activities and modes for each activity. The complexity is further enhanced by the restriction of number and type of resources for these problems. Over the past many years, a significant effort has been made to achieve optimality conditions for these types of problems. The early approaches focused on linear programming formulations and exact methods [2][3]. A priority rule-based approach can also be used to solve MMRCPSP with the assumptions that resources are renewable and may not be always available [4]. One of the key factors in the multimode scenario is the choice of most appropriate mode for execution. Ahn et al. [5] presented the concept of crashable modes to deal with this problem. The approach suggested crashing methods for the activity modes to reduce makespan. Demeulemeester et al. [6] developed a branch-and-bound algorithm to solve MMRCPSP for makespan minimization objective with the assumptions that activity duration and resource necessities are variable.

Tabu search algorithm [7] also solves the MMRCPSP. In a Tabu search approach, the activities are disintegrated in the number of modes. Scheduling is performed on fixed mode assignments. Similarly, heuristic and meta-heuristic approaches are also very well-known and efficient to deal with such NP-hard problems. A deferential evolution algorithm (DE) also deals with the MMRCPSP. The objective is the minimization of makespan. The results obtained for the DE are known to be efficient [8].

Jarboui et al. [9] proposed a combinatorial particle swarm optimization (CPSO) based method for multimode problems. The comparison with other algorithms for standard instances is performed based on average deviation from the optimal results. Similarly, Simulated annealing (SA) algorithm also serves the purpose of solving multimode problems. The search pattern in SA is based on the combination of two search loops: alternating activity and mode neighborhood exploration [10].

A Similar effort is made in another study [11] where SA serves the makespan minimization objective for multimode scenarios. Feasible list of mode assignments and activities are suggested through this approach. Elloumi et al. [12] recommended a rank centered evolutionary algorithm which considered MMRCPSP. It was based on a clustering-based fitness function. It looked for a feasible solution for minimization of makespan.

An estimation of distribution algorithm (EDA) also considered the multi-mode case of resource-constrained scheduling problem [13]. In this algorithm, mode choices are determined based on the activity-mode listing (AML) and translated and decoded to multi-mode serial schedule generation structure (MSSGS). The algorithm makes use of multimode forward and backward iterations to optimize the results. Cheng et al. [14] considered the MMRCPSP and proposed a different technique to generate optimal results. The proposed techniques included a branch and bound algorithm based on precedence trees, time window rule, and a priority rule based on simple heuristics.

A recent study addresses the MMRCPSP merged with the material ordering issue with respect to time and quantity. The study also focused on improvement in meta-heuristic techniques through hybrid search approaches. The combination of meta-heuristic algorithms includes PSO-GA, GA-GA and SA-GA. The hybridization of meta-heuristics yields near-optimal solutions [15]. Muritiba et al. [16] proposed a Path-Relinking (PR) algorithm for Multi-mode Resource-Constrained Project Scheduling Problem (MRCPSP). The algorithm travels in solution space between two solutions and performs a local search around the intermediate solutions. The algorithm was tested using benchmark instances to compare with other competitive methods from the literature.

Delgoshaei et al. [17] proposed a scheduling model based on integer programming that can schedule different activities according to execution conditions. A particular interest of this study was to solve the problem of over-allocation of resources by considering uncertain activity duration. Tirkolaee et al. [18] addressed a resource-constrained scheduling problem with multiple objectives. In this problem, each activity is performed from a set of given modes. The overall objective was to maximize the cumulative present value and minimize the time of completion. The proposed model was validated with the help of several random instances. To solve the NP-hard problems, the authors proposed two meta-heuristic techniques of non-dominant sorting genetic algorithm and simulated annealing algorithm with multiple objectives.

In most of the studies, authors have incorporated priority rules of multi-mode scheduling, however, these rules do not always produce the desired outputs. A good method based on priority rules act as bases to get better results from metaheuristic algorithms. A similar approach is adopted by Adamu et al. [19] in which priority rules are employed to calculate the primary solutions for metaheuristic algorithms. The proposed algorithm incorporates pre-calculated processing times to simplify the project data in order to accelerate the process. Subsequently, the mode assignment procedure and machine learning priority rule are utilized to generate a schedule base of schedule generation scheme. The proposed algorithm acts as an efficient startup for meta-heuristic.

From the literature review, it is evident that a significant effort has been made on multi-mode scheduling aspects. The most general approach to solve multimode problems can be summarized in two phases and can be named as a two-phase approach. In first phase a mode is selected for each activity based on predefined criteria. In the second phase the problem transforms into a single mode resource constrained project scheduling problem. The problem is then scheduled through the approaches used for generalized resource constrained project scheduling problems.

The approach presented in this paper is smart and unique compared to classical approaches in the literature in the sense that it not only searches for the best execution mode for the activity, but also involves activity shifting tactics while schedule a generation. The beauty of the heuristic is that it optimizes best mode selection as well as best activity to add in the sequence simultaneously. The Heuristic is tested for the standard cases from the Project Scheduling Problem Library (PSPLIB) generated through the problem generator Progen [20].

The rest of the paper is organized as follows. Section 2 describes the the problem with the help of a mathematical model. Section 3 describes the methodology adopted in the proposed heuristic with the help of a flow chart. The results are presented in graphical and tabular illustrations in section 4. Section 5 concludes the paper.

1.1 Problem Description

The multi-mode case of project scheduling is explained through its mathematical model. This section describes the notations and equations used in this study. A part of these notations and equation are related to general multi-mode, resource-constrained project scheduling problems and rest for them are related to additional constraints for the proposed heuristic.

A typical multimode project scheduling problem consists of i activities. Each activity i can be performed in m modes. The time required by an activity i in mode m is defined by the variable d_{im}. The problem consists of renewable and nonrenewable resource limits which are denoted by R_k^n and R_k^v respectively. The brief explanation of the variables used in the mathematical modeling is shown in showed in Table 1.

1.2 Mathematical Modeling

The objective is to minimize the project duration by reducing time t for n number of activities in the schedule with variation in the early and the latest finish times for number of available modes. The mathematical model in Equation (1) defines the objective.

$$Minimize\ z_1 = \sum_{t=EF_i}^{LF_i} tx_{imt},\ \forall m \in M_i\ i \in I \tag{1}$$

The variable x_{imt} is the binary constraint and is defined by Equation (2). If the activity i takes place in mode m and time t, then $x_{imt} = 1$.

$$x_{imt} = \begin{cases} 1, & \text{if activity is performed.} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

The other constraints for a standard multi-mode project scheduling problem are:

$$\sum_{m=1}^{M_i} \sum_{t=EF_a}^{LF_i} x_{imt} = 1,\ \forall m \in M_i,\ i \in I \tag{3}$$

$$\sum_{m=1}^{M_a} \sum_{t=EF_a}^{LF_a} tx_{amt} \leq \sum_{m=1}^{M_i} \sum_{t=EF_b}^{LF_b} tx_{imt},\quad \forall m \in M_i,\ i \in I,\ a \in P_i \tag{4}$$

$$\sum_{i=1}^{I} \sum_{m=1}^{M_i} r_{kim}^v \leq R_k^v,\ \forall m \in M_i,\ i \in I,\ k \in K_v \tag{5}$$

$$\sum_{i=1}^{I} \sum_{m=1}^{M_i} r_{kim}^n \leq R_k^n,\ \forall m \in M_i,\ i \in I,\ k \in K_n \tag{6}$$

$$x_{imt} = \{0, 1\},\ \forall m \in M_i,\ i \in I,\ t \in T \tag{7}$$

Equation (1) defines the objective of makespan minimization of the project. Equation (2) describes the binary constraints for mode executions. Equation (3) assures that a single mode is allotted to finish the activity in a certain time frame. Equation (4) defines the precedence constraints among activities. Equation (5) and (6) define the restriction on the availability of renewable and nonrenewable resources, respectively. Equation (7) defines the set of decision variables for binary constraint.

In a multi-mode project scheduling approach used in this study, the resource availability with respect to time varies as the activities are scheduled and the schedule moves forward. Equations (8) and (9) depict the resource availability constraints with respect to time.

$$\sum_{i=1}^{I} \sum_{m=1}^{M_i} r_{kim}^v \leq R_k^v(t),\ \forall m \in M_i,\ i \in I,\ k \in K_v,\ t \in T \tag{8}$$

$$\sum_{i=1}^{I} \sum_{m=1}^{M_i} r_{kim}^n \leq R_k^n(t),\ \forall m \in M_i,\ i \in I,\ k \in K_n,\ t \in T \tag{9}$$

In this scenario, an activity can be scheduled at any position in the schedule if the required resource is available for the activity. The activity is scheduled either in accordance with the finish time of the preceding activity on the network or the finish time of the preceding activity on the resource. In case the resource is not available, the activity takes time equal to the finish time of the previous activity on the resource added to the duration of the activity on the selected mode. Otherwise, the activity continues from the finish time of the previous activity on the network added to its duration. This scenario is described by Equation (10) and (11).

$$t = FT_{pap} + d_{im},\ \forall m \in M_i,\ i \in I,\ t \in T,\ a \rightarrow i \tag{10}$$

or,

$$t = FT_{par} + d_{im},\ m \in M_i,\ i\ inI,\ t\ inT \tag{11}$$

Notation	Description
$I = \{1, 2, 3, ..., a, i, ...I\}$	Set of activities of project
$M_i = \{1, 2, 3, ..., m\}$	Set of number of modes for activity i
d_{im}	Duration of activity i for mode m
t	Length of an activity in the schedule
$K_v = \{1, 2, 3, ..., k\}$	Set of nonrenewable resource
$K_n = \{1, 2, 3, ..., k\}$	Set of renewable resource
R_k^v	Predefined nonrenewable resource limit
R_k^n	Predefined renewable resource limit
$R_k^v(t)$	Availability of nonrenewable resource k at time t
$R_k^n(t)$	Availability of renewable resource k at time t
r_{kim}^v	Requirement of nonrenewable resource k to perform activity i in mode m
r_{kim}^n	Requirement of renewable resource k to perform activity i in mode m
EF_i	Earliest finish time of activity i obtained with consideration of minimum duration and exception of resource consumption
LF_i	Latest finish time of activity i obtained with consideration of minimum duration and exception of resource consumption
P_i	Set of predecessors of activity i
FT_{pap}	Finish time of activity a in accordance with the predecessor of i from P_i such that $a \rightarrow i$
FT_{par}	Finish time of activity a in accordance with the preceding activity on resource
T	Makespan of project

TABLE 1: Notations and their explanations

2 Heuristic Approach for MMRCPSP

An efficient heuristic method is proposed in this study to solve a multi-mode project scheduling problem with scarce resources. The heuristic initializes the schedule with the help of predefined values for the variables. It uses an efficient technique to sort out different modes for an activity and chooses the best mode. Furthermore, it uses efficient decisions for activity shifting without affecting the resource and precedence constraints, which optimizes the overall makespan of the project. Figure 1 depicts the proposed method in the form of a flow chart. The heuristic method defined in Figure 1 is a 3-step approach. The steps and sub-steps involved in the heuristic are described as under.

Step 1: It is the initialization phase which assures the preliminary requirements for the execution of the heuristic.

Step 1.1: The foremost step in the heuristic is to consider the mandatory input data values. These inputs consist of the number of activities, the number of modes for each activity, the resource limits, and the resource requirements for each activity.

Step 1.2: The next step is to initialize the schedule for the given statistics. This step follows scheduling an activity i in the project by setting its start time to 0.

Step 1.3: The activities initiated in the schedule go through the precedence check. If the activity does not meet the precedence criteria, it is sent back to step 1.2 and initiated in the next iterations until it meets the precedence criteria.

Step 2: In this phase, the different modes available for performing an activity are assessed and the best one is selected.

Step 2.1: This step identifies the different modes available for the activity according to the resource limits criterion for renewable and nonrenewable resources (defined in Eq. (5) and (6)).

Step 2.1: The modes which do not fulfill the resource limit criteria are ignored and the fit modes are moved to the next step.

Step 2.3: In this step, the eligible modes are assessed on the criterion of the minimum duration. The mode with minimum duration is selected.

Step 3: It is the schedule generation phase where activities are shuffled in the schedule under resource and precedence constraint.

Step 3.1: In this step the selected activity i goes through a check which determines either the finish time of the preceding activity on

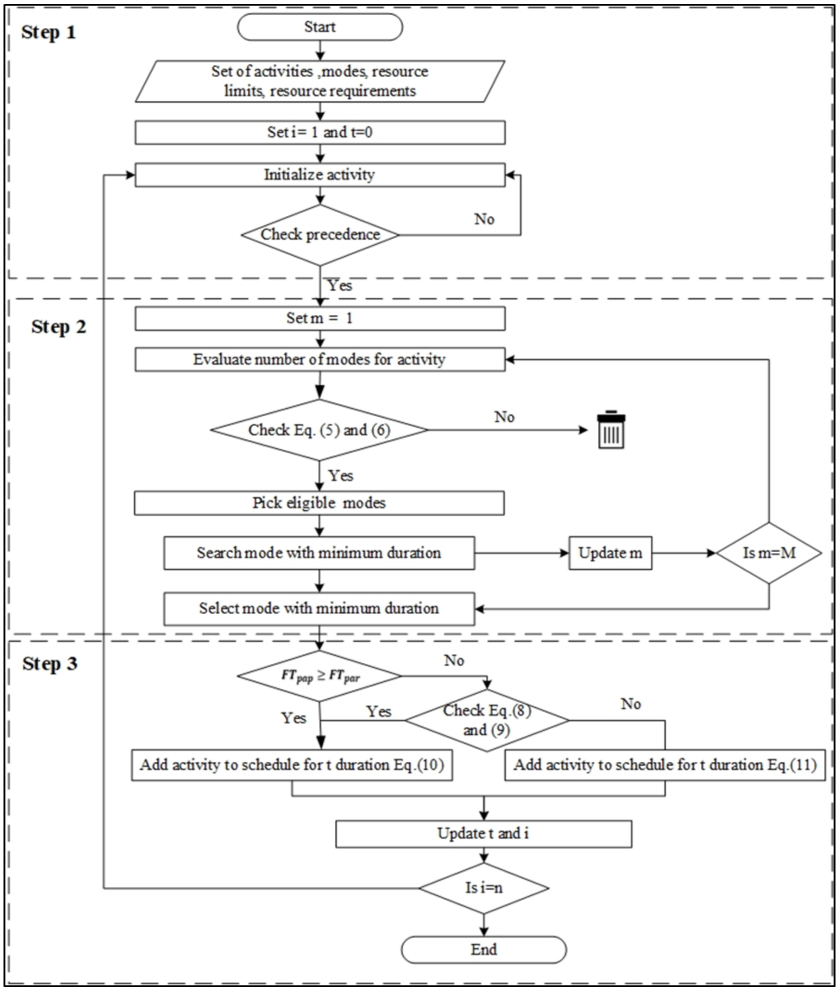

Fig. 1: Hueristic method for multimode project scheduling

the network is greater than the finish time of the preceding activity on the resource.

Step 3.2: If the condition described in step 3.1 satisfies the activity, it is added to the schedule for the time t as defined by Eq. (10), which is the finish time of the preceding activity on the network added to d_{jm}.

Step 3.3: If the condition described in step 3.1 does not satisfies the activity, it goes through another check which assures the availability of the resource with respect to time. If the resource is available, the activity is added to the schedule for the time t as defined by Eq. (10), which is the finish time of the preceding activity on the network added to d_{jm}.

Step 3.4: If the activity fails the previous two checks, it is added to the schedule for the time t as defined by Eq. (11), which is the finish time of the preceding activity on resource added to d_{jm}.

Step 3.5: The successful completion of schedule generation for activity leads to the next iteration. The activity i and time t is updated and the loop continues from step 1.2 until all activities are scheduled.

3 Computational Experiments & Results

The proposed heuristic is solved for benchmark instances in PSPLIB. The heuristic is also tested for other benchmark instances and a comparison is done against the optimal results for those instances.

3.1 Case Study

The input data and results for case study are shown in Table 2. In this table, the input data consists of activity identities, number of successors for each of activity, number of modes for each activity, renewable/nonrenewable resource limits, and the resource requirements for each activity on each mode. The results generated through the proposed heuristic give the start and finish

Input Data												
No. of Activities	**Successors**			**M**	**D**	**R1=9**	**R2=4**	**N1=49**	**N2=40**	**ST**	**FT**
1	2	3	4	1	0	0	0	0	0	0	0
2	5	6		**1**	**3**	**6**	**0**	**9**	**0**	0	3
				2	9	5	0	0	8		
				3	10	0	6	0	6		
3	10	11		**1**	**1**	**0**	**4**	**0**	**8**	0	1
				2	1	7	0	0	8		
				3	5	0	4	0	5		
4	9			1	3	10	0	0	7	3	8
				2	**5**	**7**	**0**	**2**	**0**		
				3	8	6	0	0	7		
5	7	8		1	4	0	9	8	0	3	9
				2	**6**	**2**	**0**	**0**	**7**		
				3	10	0	5	0	5		
6	10	11		**1**	**2**	**2**	**0**	**8**	**0**	8	10
				2	4	0	8	5	0		
				3	6	2	0	0	1		
7	9	10		**1**	**3**	**5**	**0**	**10**	**0**	9	12
				2	6	0	7	10	0		
				3	8	5	0	0	10		
8	9			**1**	**4**	**6**	**0**	**0**	**1**	12	16
				2	10	3	0	10	0		
				3	10	4	0	0	1		
9	12			**1**	**2**	**2**	**0**	**6**	**0**	16	**18**
				2	7	1	0	0	8		
				3	10	1	0	0	7		
10	12			1	1	4	0	4	0	12	13
				2	**1**	**0**	**2**	**0**	**8**		
				3	9	4	0	0	5		
11	12			**1**	**6**	**0**	**2**	**0**	**10**	10	15
				2	9	0	1	0	9		
				3	10	0	1	0	7		
12	0	0	0	1	0	0	0	0	0		

TABLE 2: Input data and results for the case study

time of each activity. The data values in bold text show the corresponding mode selected by the heuristic for the execution of the activity. The project makespan is 18 which is finish time of the activity 9, as highlighted in Table 2. The graphical illustration of results obtained through proposed heuristic solution for the Case study is depicted in Figure 2. Figure 2 shows the graph of resource over time for the set of renewable and nonrenewable resources in the study. The activities are assigned to respective resources with the help of the heuristic approach. The time and resource occupied by the activities on respective resources can be easily observed. The makespan of the project will be the finish time of activity 9 on renewable resource 1, as it is the last activity in the schedule among all activities on all resources. All activities are scheduled within resource limits and precedence constraints.

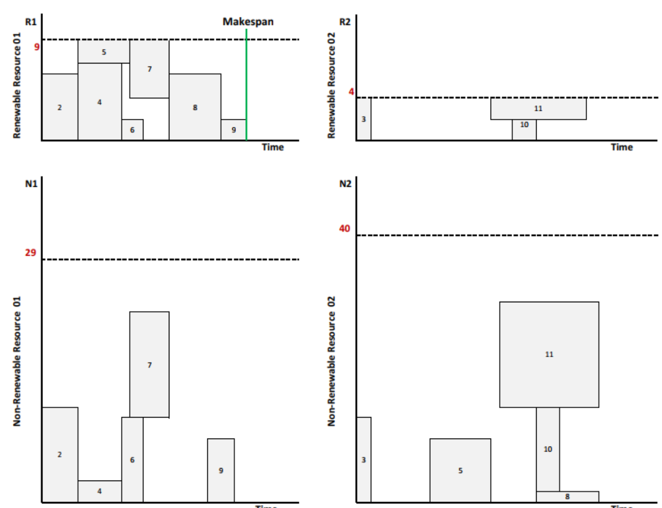

Fig. 2: Graphical explanation of results

3.2 Comparative Analysis

The proposed heuristic is solved for benchmark instances and the results are compared with the optimal results. The percentage optimality difference gives a bird eye view of the efficacy of the proposed heuristic. It can be observed that the heuristic outperforms the optimal results for one of the instances and gives similar results for the other instances. It can be further

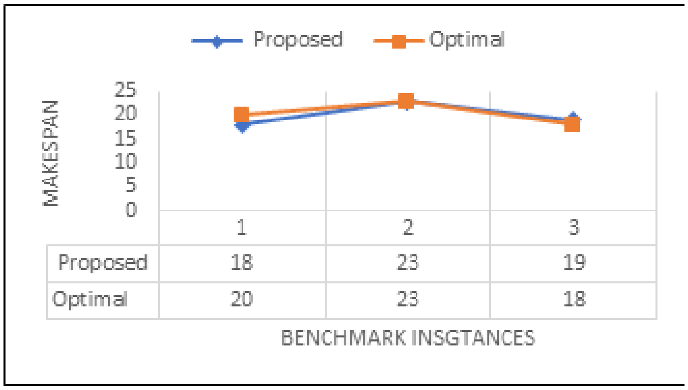

Fig. 3: Graphical illustration of comparison

observed that the heuristic is tested on 3 instances of each instance containing 10 jobs. A comparison is performed based on the percentage optimality difference for all instances. The graphical illustration for better understanding and comparative analysis is shown in Figure 3. It shows the comparison of the proposed heuristic with the optimal results. It can be observed from Figure 3 that the proposed heuristic performs very well for complex multi-mode problems. The trend lines for makespan are very near for the proposed heuristic results and the optimal results. At one of the instances, it outperforms the optimal result. The comparison of the efficiency of the proposed heuristic with optimal results validate its performance and proves that it is an efficient approach to solve multi-mode resource constrained project scheduling problems.

4 Conclusion

This study is in continuation of the efforts towards problems solving techniques for multi-mode resource constrained project scheduling problems. A novel heuristic was developed to solve this type of problems. The results obtained in the study are quite efficient in comparison to the heuristic approaches proposed in the literature. Following conclusion can be drawn from this study.

1) The heuristic developed in this paper proposes some innovative steps to reduce makespan of a project in multi-mode scenario.
2) The proposed heuristic is efficient in selection of the modes and the activity sequencing for multiple modes.
3) The heuristic can be compared and validated through other similar approaches in the literature.
4) The comparison of the proposed heuristics with the optimal results shows its efficacy.

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