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Integrated Planning and Scheduling of Multiple Manufacturing Projects Under Resource Constraints Using Raccoon Family Optimization Algorithm

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ABSTRACT Today's dynamic environment and increasing demand for highly customized products have significantly increased the number of companies operating in the project environment. Project planning and scheduling are one of the major problems faced by managers due to resource constraints. Enterprises have to execute several projects simultaneously while sharing limited resources (i.e., human resources, equipment, and budget) among the projects to effectively meet the deadlines. Therefore, this work investigates the integrated planning and scheduling problem of multiple projects with different release dates and execution modes while considering the renewable and non-renewable resource constraints. Moreover, the raccoon family optimization (RFO) algorithm is proposed to maximize the net profit while considering the early completion bonus, penalty cost, and resource costs. In the proposed RFO algorithm, greedy search and modified genetic operators are introduced to enhance the performance and efficiency. Effectiveness of the proposed RFO algorithm is compared with the genetic algorithm (GA), raccoon optimization algorithm (ROA), and artificial bee colonial (ABC) algorithm on test cases as well as an industrial case study. The results indicate that the proposed RFO algorithm outperforms the other compared algorithms, both in terms of effectiveness and efficiency.

INDEX TERMS Project planning and scheduling, multiple projects, resource constraint, execution modes, Raccoon family optimization algorithm.

I. INTRODUCTION

The business paradigm is being changed because of the change in customer behaviour and increasing demand for customization with recent technological developments. It has been observed that the number of companies structuring themselves as project organization is increasing. Therefore, the importance of effective project planning and scheduling has been significantly increased. Typical project planning and

scheduling involves the selection of projects and assignment of the start or finish time to the project activities while considering the precedence constraints [1]. In project planning and scheduling, resource-constrained project scheduling (RCPS) is one of the most important problems. RCPS is the extension of the critical path method (CPM) and program evaluation and review techniques (PERT) by incorporating the resource availability constraints [2]. In RCPS, activities consume time and certain resource capacity when being performed. Therefore, in addition to the precedence constraints and release time scheduling constraints, resource

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constraints create conflicts in the start time of activities. Thus, causing the delay in certain activities' start time due to the unavailability of resources. Renewable and non-renewable resource constraints have been used in literature frequently. Renewable resources are available in a specific capacity per unit time, while non-renewable resources are available in fixed capacity over the total duration of the project. The introduction of resource constraints increased the complexity of the problem and made it NP-hard. RCPS problems have been extensively investigated in the literature. However, it does not include other major aspects, i.e., multiple project and execution modes of real-world problems.

In RCPS, it is assumed that the activities of the projects can be completed only in one possible mode. However, in practice, multiple execution modes can be used to complete the activities. Each mode consists of a set of resources with different resource requirements and activity process time, as addressed by Afshar-Nadjafi [3]. Consequently, a real selection problem of execution of modes arises. Further, in real life, more than 90% of projects are being executed simultaneously, and 84% of companies are working in a multi-project environment [4], [5]. Concurrent execution of multiple projects can have a considerable impact on the performance of an organization such as short completion time, better resource utilization, and low management cost but at the expense of increasing the complexity at planning and scheduling stage [6], [7]. In a multi-project environment, projects have to schedule by assigning start and finish time to the various activities without exceeding the capacity of resources and allocated budgets. The integration of the multiple project scheduling and execution mode selection problems with RCPS significantly increases the complexity of the problem. It can be a very challenging task for project managers to find the optimal schedule for multiple projects with different execution modes [8]. Thus, several performance measures have been used by experts such as makespan [9]–[11], project delay [10], [12], tardiness [13], cost [14]–[16], and net profit [17]–[20] to measure the effectiveness of the planning and scheduling of projects. However, companies are more interested in maximizing the net profit as their performance usually evaluated based on the net profit value [21]. Extensive work can be found on RCPS problems. However, work on RCPS with multiple projects and execution modes is relatively scarce. Tseng *et al.* [19] maximized the weighted profit of the projects while considering the early completion bonus and late completion penalties using the parallel scheduling algorithm. Chiu *et al.* [20] presented a heuristic rule to minimize the project delay while maximizing the net present value with delay penalty cost and early completion bonus. Asta *et al.* [4] minimized the total project delay as a primary objective and makespan as a secondary objective with the project release constraint using a heuristic algorithm. Besikci *et al.* [5] modelled the problem as an integrated resource portfolio problem to minimize the total weighted tardiness of the projects using hybrid GA. Pinha *et al.* [22] minimized the total tardiness of the projects using a

simulation-based approach. Kucuksayacigil and Ulusoy [23] minimized makespan while maximizing the net present value using hybrid NSGA-II with a backwards-forward pass procedure. Geiger [24] minimized the total project delay and makespan using a solution approach based on variable neighbourhood search and iterated local search. Xu and Feng [25] developed a fuzzy model to optimize cost, makespan and quality using a hybrid particle swarm optimization algorithm based on combinatorial priority and hybrid crisp approach for uncertainties. In this research, the net profit value is maximized while considering the early completion bonus, penalty cost, and cost of resource utilization and idleness.

In order to solve the planning and scheduling problem, the researchers have developed three types of strategies (i.e., Hierarchical, Iterative and integrated approach) [26]. In the hierarchical approach, the planning problem is solved first without considering the scheduling constraints, and then scheduling problem is solved by fixing the planning decision variables [27]. This approach can lead to infeasible schedules [26], [28]. In the iterative approach, various planning solutions are found and then evaluated at the scheduling level. While in the integrated approach, the problem is formulated as a single problem with the consideration of resource constraints and costs, so there is no separation between planning and scheduling [28]. The integrated approach is complicated and hard to solve. However, it provides a quality solution in acceptable calculation time [26]. Therefore, the integrated approach for planning and scheduling of multiple projects is used in this research.

Over time, two methods (i.e., single project (SP) method and multi-project (MP) method) have been developed by researchers, which in combination with priority rules and heuristic algorithms have been used for planning and scheduling of multiple projects. In the SP method, all the projects are merged into one mega project with a single start and finish dummy activity by reducing the multiple project problem into a traditional single project scheduling problem [29]. Several researchers have used this approach to simplify the multiple project scheduling problem [11], [29], [30]. One of the significant drawbacks of this method is that the details related to individual projects cannot be retained. Further, it is unrealistically assumed that the delay penalties for all the projects are equivalent [31]. However, in the MP method, each project is considered separately with a distinct start and finish dummy activities [11]. MP method considers the projects separately, thus eliminating the drawbacks of the SP method. In combination with these methods, Petri net-based methods and various priority rules and heuristics have been proposed by the researcher for the planning and scheduling problem. Petri nets have been widely used as a tool for scheduling in literature [32]–[35]. Kao *et al.* [36] and Wu *et al.* [37] proposed the Petri net-based approaches for the planning and scheduling of multiple projects. Several researchers [38], [39] have also proposed hybrid Petri net models. One of the significant drawbacks of Petri nets is the increase in their size with the complexity problem [40]. Kruger and Scholl [11] developed

a priority rule-based procedure while Wang *et al.* [31], Browning and Yassine [41], Vazquez *et al.* [42] and Lova and Tormos [29] separately studied the performance of priority rules for multi-project scheduling problem. Lova *et al.* [8], Mittal and Kanda [15] and Kim and Leachman [43] proposed heuristic algorithms that outperform the priority rules. Tseng [19] proved that the genetic algorithm (GA) provides better results as compared to the parallel scheduling algorithm consisting of the best combination of activity and mode priority rules for scheduling multiple projects. Asta *et al.* [4] proposed a hybrid heuristic algorithm based on Monte-Carlo tree search, memetic algorithms, hyper-heuristic methods, and novel neighbourhood moves. They proved that the proposed algorithm performed better than the other solvers on the set of benchmark problems. Yang and Fu [44] proposed a multi-project scheduling method based on critical chain and evidence reasoning to determine the buffer size and locations. Zheng *et al.* [12] and Homberger [45] developed a multi-agent system based algorithms using elimination mechanism and restart evolution strategy respectively. Alongside these algorithms, several researchers [14], [23], [25], [46] have also proposed hybrid algorithms to enhance their performance. Beside these algorithms; algorithms based on the social structure and food searching behavior of animals known as swarm intelligent optimization algorithms tends to perform well for continuous as well as constrained optimization problem [47]–[49]. Therefore, in this research, raccoon family optimization (RFO) algorithm is proposed which mimic the social structure and foraging behaviour of raccoons. Raccoons' excellent ability for survival and foraging help to find better global optimal solution.

It can be summaries from the above literature that companies have to execute multiple projects simultaneously, with different release date and activity execution modes, with limited resources to succeed in today's competitive environments. Therefore, this research investigates the integrated planning and scheduling of multiple projects with different release dates and execution modes under resource constraints to maximize the net profit value while considering the early completion bonus, penalty cost, and cost of resource utilization and idleness. A novel RFO algorithm is proposed for the first time to solve this problem. To cope with the discrete nature of the current problem, and to enhance the exploration and exploitation of the proposed RFO algorithm, modified genetic and greedy search operators are introduced. Additionally, the feasibility check and repair procedures are introduced to check the constraints violation instantaneously and repair the infeasible solution. The performance of the proposed RFO algorithm is compared with the genetic algorithm (GA), raccoon optimization algorithm (ROA) and artificial bee colonial (ABC) on test case instances as well as a real-life case study.

The rest of the paper is organized as follows. The problem formulation and mathematical model are presented in section 2, while the newly proposed raccoon family

optimization algorithm (RFOA) is described in section 3. In section 4, the computational experiment and analysis of results are presented along with algorithms' comparison, while the implementation of the proposed method on a real-life case study is discussed in section 5. Finally, conclusions and future recommendations are provided in section 6.

II. PROBLEM DESCRIPTION

In this paper, integrated planning and scheduling problem of multiple projects with different release dates and execution modes under resource constraints is investigated. It is the generalization of the traditional RCPS problem in two ways. First, multiple projects P_i have to be scheduled simultaneously while sharing limited resources. So, activities must assign start and finish time while considering the resource availability. Second, an activity A_j can be performed in multiple execution modes where each mode M_m may have a set of various recourses with different resource requirements and activity process time. Two types of resources are defined: renewable resources R_r and non-renewable resources R_k^{nr} . Renewable resources are available in a specific capacity per unit time and are required by activities of the projects in a certain amount for a specific period. While non-renewable resources are available in fixed capacity over the total duration of the project. Non-renewable resources are limited for the individual project. Resources' capacities, the amount of resources required by activities and activity process time for each mode are known and deterministic. Each project has associated release time, which is the earliest time at which the project can be started. Moreover, multiple projects can be executed simultaneously based on the availability of renewable resources and project release date. However, the pre-emption is not allowed that is activities cannot be stopped once started. Integrated planning and scheduling problem of multiple projects with execution modes under resource constraint is shown in Figure 1. It can be seen from Figure 1 that how the three levels of the problem, i.e., multiple project planning, activities scheduling, and mode assignment are integrated. The project planning phase comprises levels 1 and 3 of the problem (i.e. selection of projects from the pool of available projects according to the release dates and assignment of feasible modes according to the resource's capacities). Scheduling phase (i.e. level 2), consists of the scheduling of activities of each project while considering the precedence and resource constraints. The objective of this problem is to maximize the total net profit while considering the early completion bonus, late completion penalty cost and resource cost.

A. MATHEMATICAL MODEL

In this section, a detailed mathematical model of integrated planning and scheduling problem of multiple projects with different release date and execution modes is presented. The objective is to maximize the total net profit of the multiple projects while considering the early completion bonus, late completion penalty cost and resource cost.

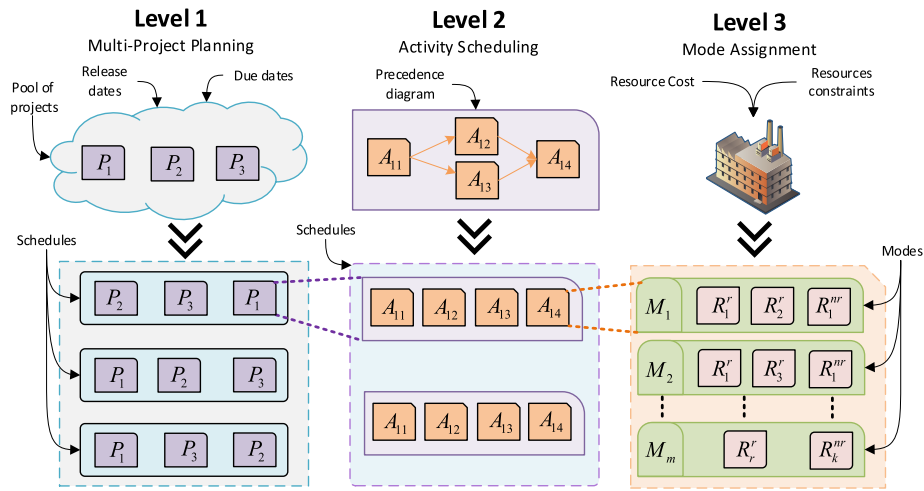


FIGURE 1. Integrated planning and scheduling problem of multiple projects with multiple execution modes.

1) INDICES

- i Index for the projects, $1 \leq i \leq I$
- j Index for the activities, $1 \leq j \leq J$
- t Index for the time, $1 \leq t \leq T$
- m Index for the modes, $1 \leq m \leq M$
- r Index for renewable resources, $1 \leq r \leq R$
- k Index for the non-renewable resources, $1 \leq k \leq K$

2) PARAMETERS

- A_{ijm}^d Process time of the activity (j) in the project (i) with the mode (m)
- Pd_i Set of all the predecessors of activities in the project (i)
- TR_r^r Total available renewable resource (r)
- TR_{ik}^{nr} Total non-renewable resource (k) available for the project (i)
- R_{ijmr}^r Amount of renewable resource (r) required by the activity (j) in the project (i) with the mode (m)
- R_{ijmk}^{nr} Amount of non-renewable resource (k) required by the activity (j) in the project (i) with the mode (m)
- RT_i Release time of the project (i)
- DD_i Due date of the project (i)
- CP_i Profit of completing the project (i)
- B_i Bonus of early completion of the project (i) for each period
- PC_i Penalty cost of the project (i) for each period
- UC_r^r Unit utilization cost of renewable resource (r)
- IC_r^r Unit idle cost renewable resource (r)
- UC_k^{nr} Unit cost of non-renewable resource (k)

3) VARIABLES

- A_{ij}^s Start time of the activity (j) of the project (i)
- A_{ij}^f Finish time of the activity (j) of the project (i)

- l_{ij} Lag in the activity (j) start time in the project (i)
- TR_{rt}^r Total renewable resource (r) available at time (t)
- RU_{ir}^r Total utilization of renewable resource (r) in the project (i)
- RI_{ir}^r Total idleness of renewable resource (r) in the project (i)
- RU_{ik}^{nr} Total non-renewable resource (k) utilization in the project (i)
- ST_i Start time of the project (i)
- FT_i Finish time of the project (i)
- NR_i Net revenue of the project (i)
- E_i Earliness of the project (i)
- Td_i Tardiness of the project (i)
- RC_i Resource Cost of the project (i)
- TC_i Total cost of the project (i)
- NP_i Net profit of the project (i)

4) DECISION VARIABLES

$$X_i^e = \begin{cases} 1 & \text{if } DD_i - FT_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$X_i^{td} = \begin{cases} 1 & \text{if } FT_i - DD_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ijm}^m = \begin{cases} 1 & \text{if the } j^{th} \text{ activity of the } i^{th} \text{ project} \\ & \text{is executed in the } m^{th} \text{ mode} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{ijt} = \begin{cases} 1 & \text{if the } j^{th} \text{ activity of the } i^{th} \text{ project} \\ & \text{is executed at time}(t) \\ 0 & \text{otherwise} \end{cases}$$

$$X_{rt}^{rs} = \begin{cases} 1 & \text{if } R_{ijmr}^r \leq TR_{rt}^r \text{ for the } m^{th} \text{ mode at} \\ & \text{time}(t) \\ 0 & \text{otherwise} \end{cases}$$

5) OBJECTIVE FUNCTION

The objective of this integrated planning and scheduling problem is to find the optimum schedule of multiple projects and their activities with feasible execution modes to maximize the total net profit. Total net profit can be measured by subtracting total project cost from total project revenue. The total revenue generated by a project depends on the completion of the project within the due date. If a project is completed earlier than the due date, a bonus for early completion of the project is awarded, while the total project cost consists of penalty cost for late completion and cost of resources used in project completion. If the project is delayed from the due date, a penalty cost is incurred for each period of delay.

$$\text{Maximize } Z = \sum_{i=1}^I NP_i \tag{1}$$

$$NP_i = CP_i + B_i \cdot E_i - TC_i \tag{2}$$

$$E_i = |DD_i - FT_i| \cdot X_i^e \tag{3}$$

$$TC_i = PC_i \cdot Td_i + RC_i \tag{4}$$

$$Td_i = |FT_i - DD_i| \cdot X_i^{td} \tag{5}$$

$$RC_i = \sum_{r=1}^R (UC_r^r \cdot RU_{ir}^r + IC_r^r \cdot RI_{ir}^r) + \sum_{k=1}^K UC_k^{nr} \cdot RU_{ik}^{nr} \tag{6}$$

$$RU_{ir}^r = \sum_{j=1}^J \sum_{m=1}^M A_{ijm}^d \cdot R_{ijmr}^r \cdot X_{ijm}^m \cdot Y_{ijt} \quad \forall \{t = 0, 1, 2, \dots, T\} \tag{7}$$

$$RI_{ir}^r = \sum_{j=1}^J \sum_{m=1}^M (TR_{rt}^r - A_{ijm}^d \cdot R_{ijmr}^r) \cdot X_{ijm}^m \cdot Y_{ijt} \quad \forall \{t = 0, 1, 2, \dots, T\} \tag{8}$$

$$TR_{rt}^r = TR_r^r - \sum_{i=1}^I \sum_{j=1}^J \sum_{m=1}^M X_{ijm}^m \cdot Y_{ijt} \quad \forall \{t = 0, 1, 2, \dots, T\} \tag{9}$$

$$RU_{ik}^{nr} = \sum_{j=1}^J \sum_{m=1}^M R_{ijmk}^{nr} \cdot X_{ijm}^m \tag{10}$$

Equation (1) indicates the objective function, which is used to maximize the net profit of multiple projects. Equation (2) is used to calculate the net profit value of the project (i). Equation (3) is used to calculate the earliness of the project (i). Equation (4) indicates that the total cost is equal to the penalty cost and resource cost. Equation (5) is used to calculate the penalty cost. Equation (6) indicates that the total cost of the resources of the project (i) is the sum of renewable resource utilization and idle cost and non-renewable resource utilization cost. Equation (7) is used to calculate the total utilization of renewable resource (r) in the project (i). Equation (8) indicates that the total idleness of renewable resource (r)

in the project (i). Equation (9) is used to measure the total renewable resource (r) available at a time (t). Equation (10) is used to measure the non-renewable resource (k) utilization in the project (i).

6) CONSTRAINTS

Constraints used in the current problem are given in (11) to (22).

$$RU_{ik}^{nr} \leq TR_{ik}^{nr} \tag{11}$$

$$\sum_{j=1}^J \sum_{m=1}^M R_{ijmr}^r \cdot X_{ijm}^m \cdot Y_{ijt} \leq TR_{rt}^r \quad \forall \{t = 0, 1, 2, \dots, T\} \tag{12}$$

$$A_{ij}^f \leq A_{ij'}^s, \quad \forall (j, j') \in Pd_i \tag{13}$$

$$\sum_{m=1}^M X_{ijm}^m = 1 \tag{14}$$

$$FT_i = \max(A_{ij}^f) \quad \forall \{j = 1, 2, \dots, J\} \tag{15}$$

$$ST_1 = 0 \tag{16}$$

$$ST_i \geq RT_i \tag{17}$$

$$A_{ij}^f = A_{ij}^s + \sum_{m=1}^M A_{ijm}^d \cdot X_{ijm}^m \tag{18}$$

$$A_{ij'}^s \geq \max(A_{ij}^f) + l_{ij'} \quad \forall (j, j') \in Pd_i \tag{19}$$

$$A_{(i+1)1}^s \geq \max\{ST_i, A_{i1}^s\} + l_{(i+1)1} \quad \forall \{j = 1, 2, \dots, J\} \tag{20}$$

$$l_{ij} = \max\left(\sum_{t=0}^T Y_{ijt} \cdot X_{rt}^{rs}\right) \quad \forall \{r = 1, 2, \dots, R\} \tag{21}$$

$$\sum_{t=0}^T Y_{ijt} = 1 \quad \forall \{j = 1, 2, \dots, J\} \tag{22}$$

Equation (11) is the non-renewable resource constraint which indicates that the total non-renewable resource (k) consumption must be less than or equal to the total available global resource. Equation (12) is the renewable resource constraint, which ensures that the consumption of renewable resource (r) does not exceed the total available renewable resource at a time (t). Equation (13) is the precedence constraint, which ensures that the activity (j') can only start if all of its predecessors' activities (j) have been completed. Equation (14) ensures that each activity can be performed only in one mode and mode switching is not allowed after the start of an activity. Equation (15) indicates that the finish time of the project (i) is equal to the maximum of activities' finish time that is the last activity of the project (i). Equation (16) ensures that the start time of the first project is zero. Equation (17) ensures that the project cannot start before its release time. Equation (18) is used to measure the finish time activity (j) in the project (i). Equation (19) indicates that the start time of the activity (j') is equal to the maximum of the finish time of activity (j) plus lag (l) due to resource unavailability. Here activity (j)



FIGURE 2. Social behaviour of Raccoons; (a) Raccoon family in a den, (b) Kids following mother, (c) Raccoon family foraging, (d) Raccoon examining food.

is the predecessor of the activity (j'). Equation (20) is used to measure the start time of the first activity of the project ($i + 1$) which is equal to the maximum of the project release time and start time of the first activity in the project (i) plus lag (l) due to resource unavailability. Equation (21) is used to measure the lag in the activity start time due to resource unavailability. Equation (22) ensures that the activity (j) in the project (i) can be scheduled only once.

III. RACCOON FAMILY OPTIMIZATION (RFO) ALGORITHM

The raccoons are medium-sized mammals that can easily adapt to any environment. In some studies, raccoons were able to unlock the complex locking mechanisms in fewer tries. Moreover, it is discovered that raccoons can remember solutions to the task, events and can discriminate objects even three to four years after the initial short learning phase [50]. A raccoon has three distinct features: facemask, ringed tail and most importantly dexterous front paws. This hypersensitive paw is used for foraging as it has more touch receptors than any other part of its body. This is the main reason for the raccoons being seen as rubbing the food and sometimes washing in water to increase the tactile sensitivity by softening the hard layer of the paws. Additionally, the large portion of the processing area in the brain is dedicated to its paws. So, raccoons examine the food more carefully with their front paws. Their eyes, along with a strong sense of smell, are another tool for foraging. These characteristics make them extremely successful in foraging and adapting to new environments [51]. Initially, raccoons are considered as solitary species; however, later studies discovered that related females live in a fission-fusion society. However, the most common social grouping among raccoons is of the mother and her kids of the years [52]. The social behavior of raccoons is shown in Figure 2 [53], [54]. Kids follow their mother and

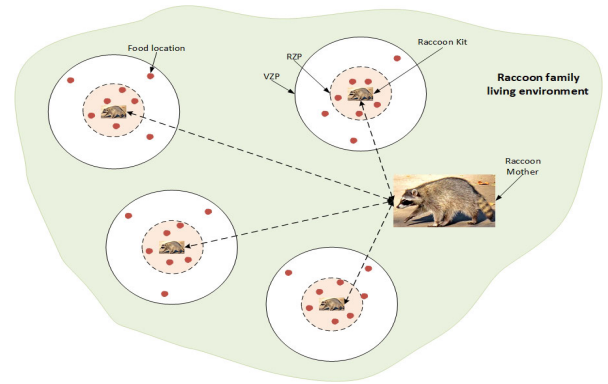


FIGURE 3. Raccoon family foraging behaviour in a living environment.

learn foraging techniques. After learning the techniques, they can forage on their own and update their mother about the possible food locations.

The excellent abilities of these creatures to quickly adapt to the new environment, finding food, long memory, problem-solving skills, and family group lead to the development of a raccoon family optimization (RFO) algorithm. This algorithm is specifically based on the model proposed by Koohi et al. [51] for the foraging behaviour of Raccoon. The living environment of the animal is considered as fitness function solution domain of the problem, while food represents various possible solution which is scattered throughout the living environment. Kids follow their mother to find the best possible solution (food). Each raccoon utilizes its touch and visual abilities to search for the food in two different sets of zones, which are called as reachable zone population (RZP) and visible zone population (VZP). After finding the location of food, they update their mother (group leader) about the good location of food available in their environment. Raccoon family foraging behaviour in the living environment is given in Figure 3. The original raccoon optimization algorithm was proposed for the optimization of continuous problems while considering only one raccoon responsible for foraging. However, the proposed algorithm considers a family of raccoons in which each member (kid) is responsible for foraging and bring food. Their mother act as a group leader who is responsible for the decision-making about the global optimum solution and migration. So, the proposed algorithm is divided into three phases: The initialization phase, the global optimization phase, and local optimization phase. Flowchart of the raccoon family optimization algorithm (RFOA) is given in Figure 4. The current integrated planning and scheduling problem of multiple projects is discrete. Therefore, new food representation is introduced, which consists of three parts: projects, activities and modes. The first vector in Figure 5 represents the projects while the second and third vectors represent the activities and modes respectively. The food location representation of all three levels is shown in figure 5.

A. INITIALIZATION PHASE

Initialization is the first stage of the proposed algorithm. In this stage, the algorithm’s parameters are set along with

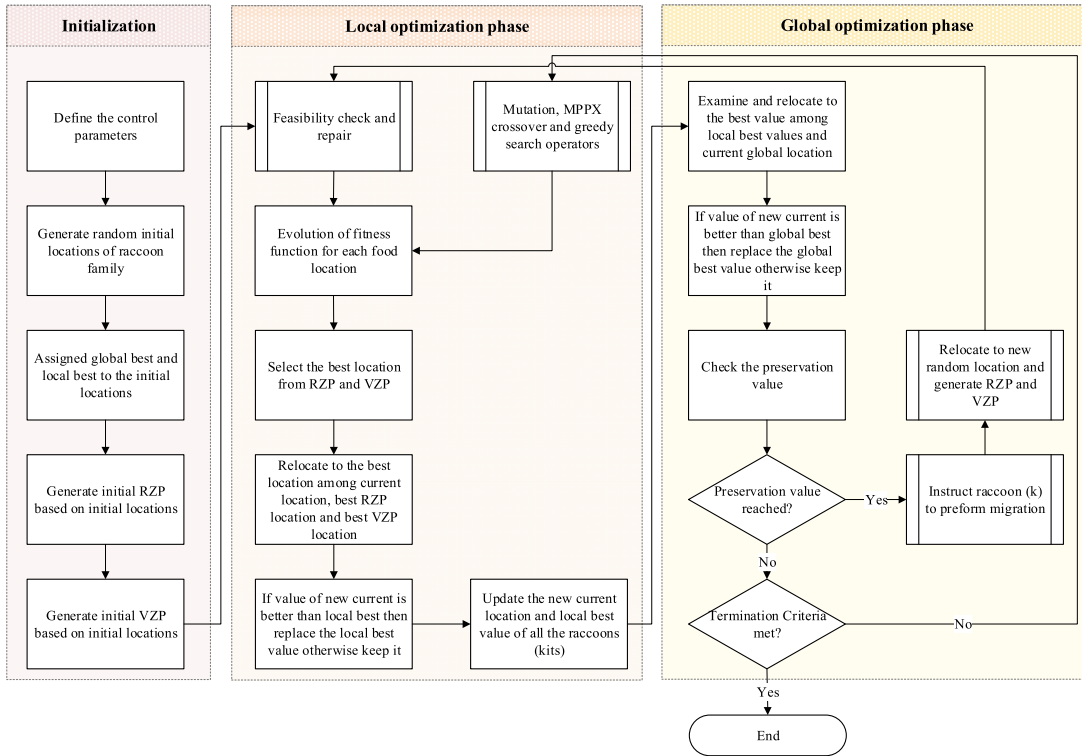


FIGURE 4. Flowchart of the raccoon family optimization algorithm (RFOA).

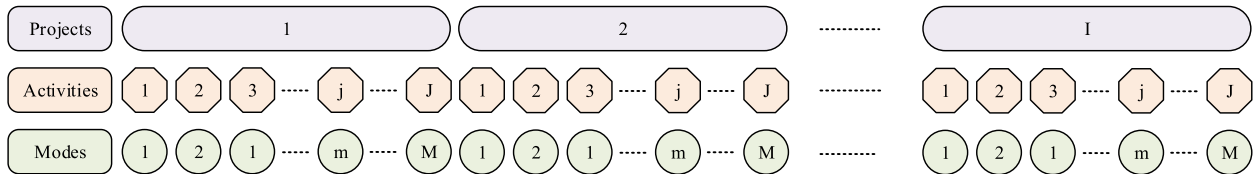


FIGURE 5. Food location representation of all three levels.

the formation of the initial population. Parameters control the general behaviour of the algorithms. There are three steps for the initialization of the RFOA. In the first step, parameters are defined while in the second step, random locations are assigned to the raccoon family in the solution domain. The initial location of the mother and k numbers of kids in the iteration $i, i \in \{0, 1, \dots, NI\}$ are denoted as g_i and loc_{ki} respectively. This initialization is considered as iteration zero, so the initial locations of the family are g_0 and loc_{k0} . Because of the good memory of the raccoons, they can remember the best food location throughout their life span. Best food location for mother raccoon and raccoon kids are called as global optimum G_{opt} and L_k^{opt} respectively. In the initialization stage, the current random locations of the family are set to G_{opt} and L_k^{opt} respectively. In the third step, the initial population is generated. This algorithm uses the two different sets of populations that are reachable zone population (RZP) and visible zone population (VZP). Each population contains a set of possible solution which is generated using the information from the initial locations of the mother and her kids. RZP

represents the set of possible food items around each raccoon that it can reach with its paws. There is an enormous amount of solutions in that area but only a certain number of solutions $N_{reachable}$ can be selected for examination. Therefore the initial reachable zone population RZP_0 is given in (23).

$$RZP_0 = \{r_0, r_1, \dots, r_{N_{reachable}}\} \tag{23}$$

Here $r_i, \forall i \in \{0, 1, \dots, N_{reachable}\}$ are the random food locations which indicate the candidate solution. RZP is very important as raccoon mostly rely on the hypertensive paws for precise examination of the foods.

After the initialization of RZP, the visible zone population (VZP) is generated. This population consists of the set of possible foods (solutions) visible to the raccoon's eyes. It consists of $N_{visible}$ number of possible foods (solutions) which must not be inside RZP. The initial visible zone population (VZP_0) is defined in (24).

$$VZP_0 = \{v_0, v_1, \dots, v_{N_{visible}}\} \tag{24}$$

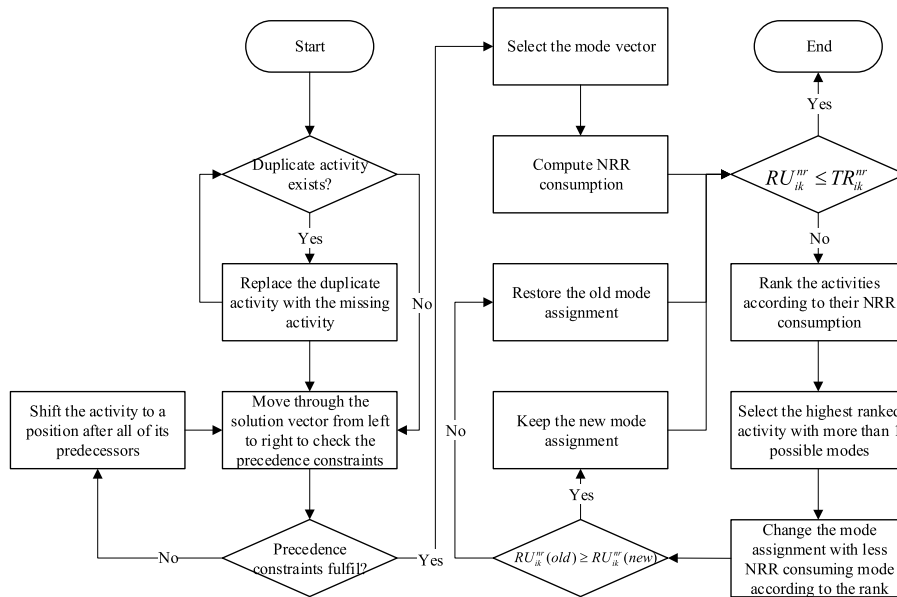


FIGURE 6. Flowchart for precedence and mode feasibility check & repair procedures (PMFCRP).

Here $v_i, \forall i \in \{0, 1, \dots, N_{visible}\}$ are random food locations in raccoons' visible range, which are the representation of possible candidate solutions. The number of possible candidate solutions in RZP must be greater than VZP as the raccoon has weak eyesight and highly sensitive paw. It is defined in (25).

$$N_{reachable} > N_{visible} \quad (25)$$

The initial population may consist of some infeasible food locations as the integrated planning and scheduling problem of multiple projects is discrete with precedence and resource constraints. Precedence and mode feasibility check & repair procedures (PMFCRP) is introduced to check the feasibility of the food location. PMFCRP consists of two-part; precedence feasibility check & repair procedure (PFCRP) and mode feasibility check & repair procedure (MFCRP). In PFCRP, start from left to right while checking the precedence constraint violation. If there is precedence constraint violation, activity is moved to the right till all its predecessors are completed. While in MFCRP, NRR consumption for every food source is calculated. If consumption is more than total NRR capacity, than activities are ranked according to their NRR consumption value and highest-ranked activity with more than one possible mode is select. After activity selection, mode assignment is changed to a new mode assignment, which consumes less NRR. This procedure is repeated until NRR consumption is less than the total NRR capacity. Flowchart for the PMFCRP is given in Figure 6.

B. LOCAL OPTIMIZATION PHASE

The local optimization phase is the second and most crucial phase of this algorithm, which is performed in each iteration $i, i \in \{0, 1, \dots, NI\}$. This phase consists of three steps:

the evolution of fitness function, relocation of raccoon and generation of the next population. First, the fitness function of all the possible candidate solutions is examined. Secondly, the best value of the fitness functions related to the current location $loc_{k(i-1)}$, the best value R_{ki}^{best} of the RZP and the best value V_{ki}^{best} of VZP is selected. Then the raccoon (kid) moves to the best value among these locations. This can be represented by (26).

$$f(loc_{ki}) = \max \left\{ f(loc_{k(i-1)}), f(R_{ki}^{best}), f(V_{ki}^{best}) \right\} \quad (26)$$

After relocation, the value of the current location loc_{ki} is evaluated against local optimum value L_k^{opt} , and the one with the best fitness value is assigned L_k^{opt} . This is defined in (27). The kids update the mother about the new current location loc_{ki} and local optimum location L_k^{opt} for the global optimization phase.

$$L_k^{opt} = \begin{cases} loc_i & \text{iff } (loc_i) > f(L_k^{opt}) \\ L_k^{opt} & \text{otherwise} \end{cases} \quad (27)$$

Thirdly, the new population is generated. At this step, greedy search operator (GSO) and genetic operators i.e. crossover and mutation, are introduced to generate the new possible candidate solutions in RZP and VZP. Genetic operators help to increase the local search space while the GSO helps to find the best solution quickly. As this problem is integrated planning and scheduling of multiple projects with various execution modes under resource constraints, so these search operators are being performed at various levels. Greedy search operator is applied at level 3 (mode assignment) in which a set of renewable and non-renewable resources is assigned to the project activities. Steps for greedy search are as given below:

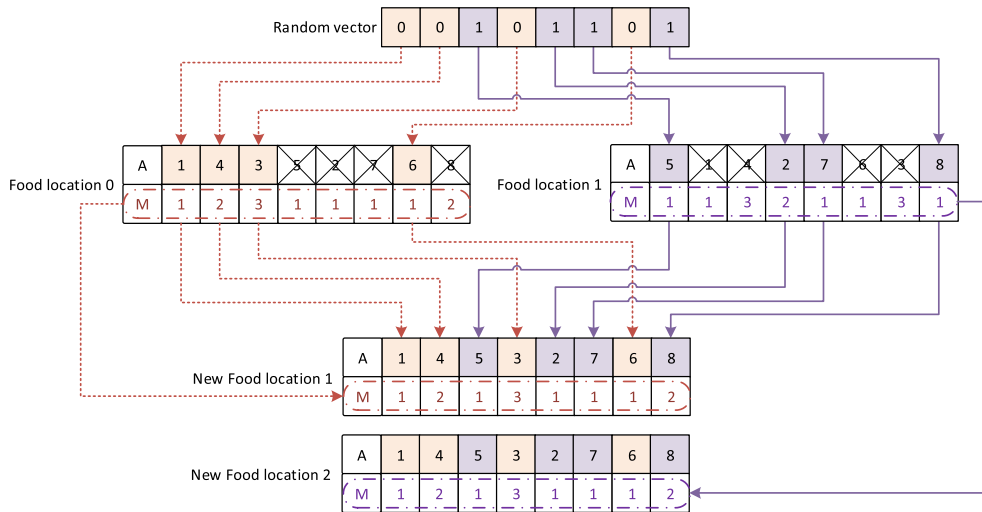


FIGURE 7. The procedure of modified precedence preservative crossover.

- 1) Randomly select a mode vector
- 2) Identify and select the resource bottleneck activity with more than one mode.
- 3) Calculate the cost of other available modes for the selected activity.
- 4) Change the mode assignment such as the resource consumption of new mode is less than the previous mode.

Further, the modified precedence preservative crossover (MPPX) is applied to the activities and mode’s vectors that is the second level of the problem. In MPPX, a random binary vector of length n equals to the length of activities’ vector is generated for selection of food location element for new food location generation. Here, 0 and 1 represent the first and second food location respectively. These numbers represent the sequence in which elements are removed from food locations and placed in a new food location vector. Starting from left, an element is selected according to the order of random vector and removed from both food location vectors then place in a new food location vector. This step is repeated until both food location vectors become empty. After the allocation of activities’ elements to new food location vector, respective modes from food locations 0 and 1 are assigned to the activities to generate new food locations 1 and 2 respectively. Further, the procedure of MPPX is illustrated in Figure 7. Finally, on the first level of the problem that is multiple project scheduling, a simple swap mutation genetic operator is applied to generate a new food location.

C. GLOBAL OPTIMIZATION PHASE

In the global optimization phase, the group leader (female raccoon) gets the information about the best food location (candidate solution) from the kids and updates its location. The group leader is responsible for the final decision making

and provides guidance about relocation and kids follow her instructions.

The group leader examined her current location g_{i-1} and the updated local optimum location L_k^{opt} of the kids. Then the group leader moves to the best location among these locations. This behaviour is modelled by (28) and (29).

$$h = \max \{f(L_k^{opt})\} \quad \forall \{k = 1, 2, \dots, K\} \quad (28)$$

$$f(g_i) = \max \{f(g_{i-1}), h\} \quad (29)$$

After the relocation of the group leader, the current location g_i is also examined against the global optimum value G_{opt} and the best value is assigned as global optimum value. This is defined in (30).

$$f(G^{opt}) = \max \{f(G^{opt}), f(g_i)\} \quad (30)$$

Besides the new local optimum location L_k^{opt} , the group leader also received information about the new current location loc_{ki} . The group leader is also responsible for the decision-making process for the migration of a raccoon that is if the current location loc_{ki} of a raccoon (kid) does not change for a certain number of iteration, then it is assumed that the best solution has been reached. In order to avoid stuck in local optimum and to minimize the premature convergence, preservation n_{pres} and migration factor (MF) are defined to facilitate the decision-making process of the group leader. For the initial step, n_{pres} is set to zero, but its value increased by one if the location does not change and again set to zero if the location changed as given in (31).

$$n_{pres} = \begin{cases} n_{pres} + 1 & \text{if } loc_i = loc_{(i-1)} \\ 0 & \text{otherwise} \end{cases} \quad (31)$$

When $n_{pres} = MF$ the group leader instructs the raccoon (kid) to perform migration that means raccoon (kid) is relocated to the new random location outside of its RZP and VZP. After

the migration n_{pres} is set to zero. As previously discussed, that raccoon has a very good memory and it always remembers the best solution L_k^{opt} , so if raccoon relocated to the worst location then this move will not affect the local optimum location L_k^{opt} . The process of local and global optimization is repeated NI number of iterations until termination criteria is met.

IV. COMPUTATIONAL EXPERIMENT AND RESULTS

In this section, test cases are defined, and the Taguchi method is used to fine-tune the parameters of the proposed RFO algorithm along with the other three famous algorithms that are GA [5], ABC [55] and ROA [51]. However, the experiment design only for the proposed RFO algorithm is present. In this section, the proposed RFO algorithm is used to solve the test cases. Moreover, the results of each case solved by the proposed RFO algorithm is also presented in this section. The results of the proposed algorithm are compared with the other algorithms as mentioned above. As per our knowledge, the proposed RFO algorithm is novel to solve this integrated planning and scheduling problem of multiple projects with execution modes under resource constraints. Thus, the proposed RFO algorithm and other algorithms as mentioned above are programmed in MATLAB™ R2018b and run on a system with Core I5-5200 U, 2.20 GHz and 8.00 GB memory. Each algorithm is run intedly while the initialization of each algorithm is kept the same to avoid the effect on the performance of the algorithms. In order to obtain reliable data, all algorithms are run ten times on each case and maximum value among different run is recorded. The performance of the algorithms is compared based on various metrics, which include average relative percentage deviation (ARPD), convergence, ANOVA analysis and robustness of solutions.

A. TEST CASES

In order to evaluate the performance of the proposed RFOA algorithm, MISTA [10] benchmark instances are used. They combined single project instances from J10, J20 and J30 cases of PSPLIP [56] to generate multiple projects' networks with multi-mode. As single projects are combined with multiple projects, so release date and resource capacities are specified. Since these instances did not have any cost date, so the cost assignment technique is adopted from Yue et al. [49]. The characteristics of the cases are given in Table 1.

B. PARAMETER TUNING WITH TAGUCHI METHOD

The performance of the algorithm highly depends upon the correct selection of parameters. Algorithms behave differently for different parameters. Therefore, in order to get optimal solutions for a specific problem, it is essential to select and fine-tune the parameters. In this research work, Taguchi method along with the orthogonal arrays is used to investigate the effects of five parameters of the proposed RFOA such as the number of kids (k, migration factor (MF),

TABLE 1. Characteristics of the cases.

Problem Set	Projects	Total activities	Modes	Renewable resource	Non-renewable resource
Case 1	2	24	3	2	4
Case 2	2	44	3	2	4
Case 3	2	64	3	2	4
Case 4	5	60	3	2	10
Case 5	5	110	3	2	10
Case 6	5	160	3	2	10
Case 7	10	120	3	2	20
Case 8	10	220	3	2	20
Case 9	10	320	3	2	20
Case 10	10	320	3	2	20

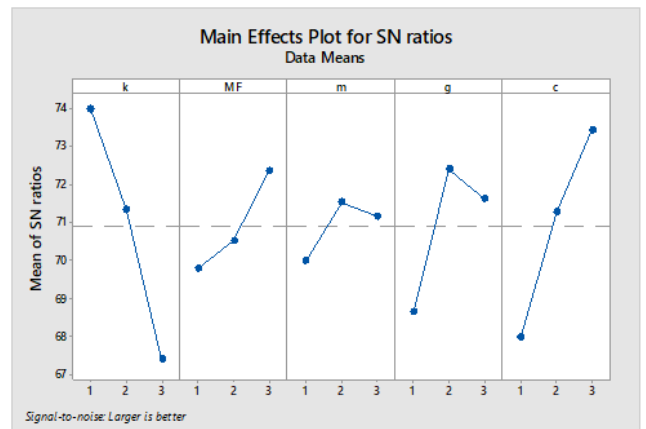


FIGURE 8. Effects of the parameter on the performance of the algorithm (a) main effect plot for means (b) main effect plot for S/N ratios.

TABLE 2. Parameters used for proposed RFO algorithm.

Parameters	Value
Number of kids (K)	3
Reachable zone food source ($N_{reachable}$)	80
Visible zone food source ($N_{visible}$)	20
Migration factor (MF)	150
Mutation rate (m)	0.2
Crossover rate (c)	0.8
Greedy search operator rate (g)	0.4
Unit record time (t)	0.5 sec

mutation (m), crossover (c) and greedy search operator (g). Further, each parameter is considered with three different levels [$k \in \{3, 5, 10\}$, $MF \in \{50, 100, 150\}$, $m \in \{0.1, 0.2, 0.3\}$, $g \in \{0.2, 0.4, 0.6\}$, $c \in \{0.4, 0.6, 0.8\}$]. As this problem contained five parameters and three-level, so orthogonal array $L_{27}(3^5)$ is used, which means 27 experiments with various values of parameters for test cases need to be tested. In this experiment design, the algorithm was run ten times for each experiment and the corresponding values of the objective function (response) are recorded to obtain reliable data. Response value from each experiment is converted into a signal-to-noise (S/N) ratio. For the design of the experiment and Taguchi analysis, MINITAB™ 18 is used. S/N ratios are given in Figure 8, which shows the effect of parameters on the performance of the algorithm. Optimal

TABLE 3. Comparison of ARPD values of algorithms at various intervals.

Problems set	Algorithms	Time interval (sec)					Average
		200	400	600	800	1000	
1	RFOA	0	0	0.0020	0	0	0.0004
	ROA	0.0080	0.0002	0	0.0480	0.0480	0.0208
	ABC	0.1891	0.1445	0.1462	0.1964	0.1964	0.1745
	GA	0.0940	0.0666	0.0684	0.1232	0.1232	0.0951
2	RFOA	0	0.0125	0	0	0	0.0025
	ROA	0.0075	0	0.0926	0.0867	0.0867	0.0547
	ABC	0.1667	0.0835	0.1475	0.1475	0.1475	0.1386
	GA	0.0214	0.0297	0.1195	0.0917	0.0917	0.0708
3	RFOA	0.0188	0	0	0	0	0.0038
	ROA	0	0.0411	0.0411	0.0411	0.0411	0.0329
	ABC	0.0825	0.1202	0.1202	0.1202	0.0942	0.1074
	GA	0.2020	0.1689	0.1168	0.0948	0.0948	0.1354
4	RFOA	0	0	0	0	0	0
	ROA	0.2704	0.3999	0.4120	0.4120	0.4120	0.3813
	ABC	0.8157	0.7838	0.6764	0.6764	0.6764	0.7258
	GA	0.1847	0.3652	0.3777	0.3777	0.3701	0.3351
5	RFOA	0	0	0	0	0	0
	ROA	0.3948	0.2854	0.2854	0.3598	0.3598	0.3370
	ABC	0.6943	0.6943	0.6943	0.7262	0.7262	0.7071
	GA	0.6274	0.1760	0.1726	0.2589	0.2589	0.2988
6	RFOA	0	0	0	0	0	0
	ROA	0.5028	0.5326	0.6094	0.2452	0.2452	0.4270
	ABC	0.5090	0.4272	0.5214	0.5445	0.5445	0.5093
	GA	0.5709	0.5032	0.5463	0.5683	0.4039	0.5185
7	RFOA	0	0	0	0	0	0
	ROA	1.9998	2.5384	1.9250	1.9250	1.9250	2.0627
	ABC	3.5817	4.6067	4.4467	3.9590	3.9590	4.1106
	GA	2.7081	2.7533	2.7533	1.8791	1.8791	2.3946
8	RFOA	0	0	0	0	0	0
	ROA	3.2111	1.4960	1.1197	1.0272	1.0214	1.5751
	ABC	3.7731	3.4510	3.4510	3.3251	3.3251	3.4650
	GA	3.0861	2.7807	2.4448	2.1480	1.9107	2.4741
9	RFOA	0	0	0	0	0	0
	ROA	3.0895	1.1765	1.0482	1.0482	1.0482	1.4821
	ABC	2.8154	2.0676	1.9115	1.8550	1.8550	2.1009
	GA	2.9983	1.3741	1.2611	1.2606	0.9507	1.5689
10	RFOA	0	0	0	0	0	0
	ROA	4.9385	22.0296	1.4271	1.1534	1.1094	4.1562
	ABC	5.4709	40.8531	4.5177	4.5177	4.5177	9.7871
	GA	5.8386	42.3434	4.9702	3.7208	2.8270	9.6046

TABLE 4. Available capacity of renewable and non-renewable resources.

No.	Resources	Capacity	Type
1	Machine Type 1 (R1)	3	Renewable
2	Machine Type 2 (R2)	3	Renewable
3	Machine Type 3 (R3)	3	Renewable
4	Machine Type 4 (R4)	2	Renewable
5	Machine Type 5 (R5)	2	Renewable
6	Machine Type 6 (R6)	3	Renewable
7	Machine Type 7 (R7)	1	Renewable
8	Machine Type 8 (R8)	2	Renewable
9	Operators Type 1 (R9)	8	Renewable
10	Operators Type 2 (R10)	8	Renewable
11	Material Type 1 (NR1)	Project dependent	Non-renewable
12	Material Type 2 (NR2)	Project dependent	Non-renewable

level of each key parameter can be seen from the figure 8 (i.e. k = 3, MF = 150, m = 0.2, g = 0.4, c = 0.8). After tuning by the Taguchi method, the selected combination of parameters used for the proposed RFO algorithm is given in Table 2.

C. COMPARISON OF RESULTS

In this section, test instances from the previous section are solved by the proposed RFO algorithm along with ROA, ABC and GA. In literature, various techniques have been used to compare the performance of the algorithms, i.e., ARPD values [48], [57], convergence [48], ANOVA analysis [58] and robustness [48], [58]. Therefore, these techniques are selected as the performance metric for the comparison of the proposed RFO algorithm with the other above-mentioned algorithms. For each algorithm, the objective function value is selected at specific time intervals to calculate the ARPD values. ARPD values for the algorithms are calculated using (32).

$$APRD = \frac{Obj_b - Obj_c}{Obj_b} \tag{32}$$

Here Obj_b is the best objective function value among compared algorithms while Obj_c is the objective function value of the under examine algorithm. ARPD values of

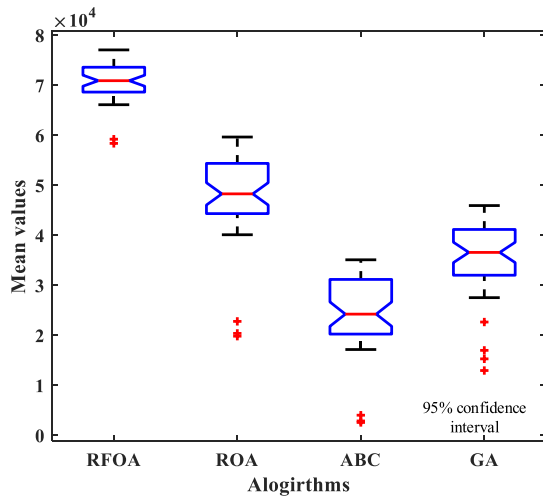


FIGURE 9. Mean values and robustness of the solutions at 95% confidence interval.

TABLE 5. Characteristics of the project 1.

Activities	Successors	Modes	Process time
1	2	1	0
2	3, 13, 14, 17	1	136
3	4, 6, 8	1	243
4	5	1	158
5	10	2	392
6	7	1	76
7	9	1	792
8	9	2	167
9	10	1	36
10	11	2	234
11	12	1	138
12	16	2	120
13	15	1	239
14	15	1	325
15	16	2	206
16	20	1	114
17	18, 19	1	131
18	20	2	152
19	20	1	87
20	21	2	204
21	-	1	0

the objective function obtained from the algorithms at various time intervals for each instance are given in Table 3. It can be seen from Table 3 that proposed RFO algorithm attained minimum ARPD values of each problem for most of the time interval except for problem 1 (interval 600 sec), problem 2 (interval 400 sec) and problem 3 (interval 200 sec) where RO algorithm obtain a better solution. The average of the ARPD values at various time intervals is

TABLE 6. Characteristics of the project 2.

Activities	Successors	Modes	Process time
1	2, 10	1	0
2	3, 6	1	270
3	4	1	195
4	5	1	171
5	9	1	147
6	7	1	154
7	8	1	100
8	9	2	64
9	12	1	221
10	11	2	120
11	12	3	234
12	13	1	72
13	-	1	204
14	-	1	618
15	-	1	30
16	-	2	270
17	-	1	114
18	-	2	204
19	-	1	0

TABLE 7. Characteristics of the project 3.

Activities	Successors	Modes	Process time
1	2, 7	1	0
2	3, 13	1	330
3	4	1	382
4	5	1	136
5	6	2	317
6	10	1	558
7	8	1	150
8	9	1	146
9	10	1	280
10	11	1	72
11	12	2	120
12	19	1	120
13	14	1	64
14	15	2	221
15	16, 17, 20	1	105
16	18	1	236
17	18	2	744
18	19	1	111
19	25	1	126
20	21, 23	1	78
21	22	1	174
22	25	1	150
23	24	2	300
24	25	1	191
25	26	1	106
26	-	1	67
27	-	2	150
28	-	1	137
29	-	1	68
30	-	2	199
31	-	1	180
32	-	2	300
33	-	1	0

given in the last column of Table 3, which validates that the RFO algorithm performed best among the compared algorithms.

To further validates the effectiveness of the proposed RFO algorithm, its performance is examined based on the ANOVA analysis and solution robustness with other compared algorithms. ANOVA analysis is performed at the confidence interval of 95%. The mean value and robustness of the solutions

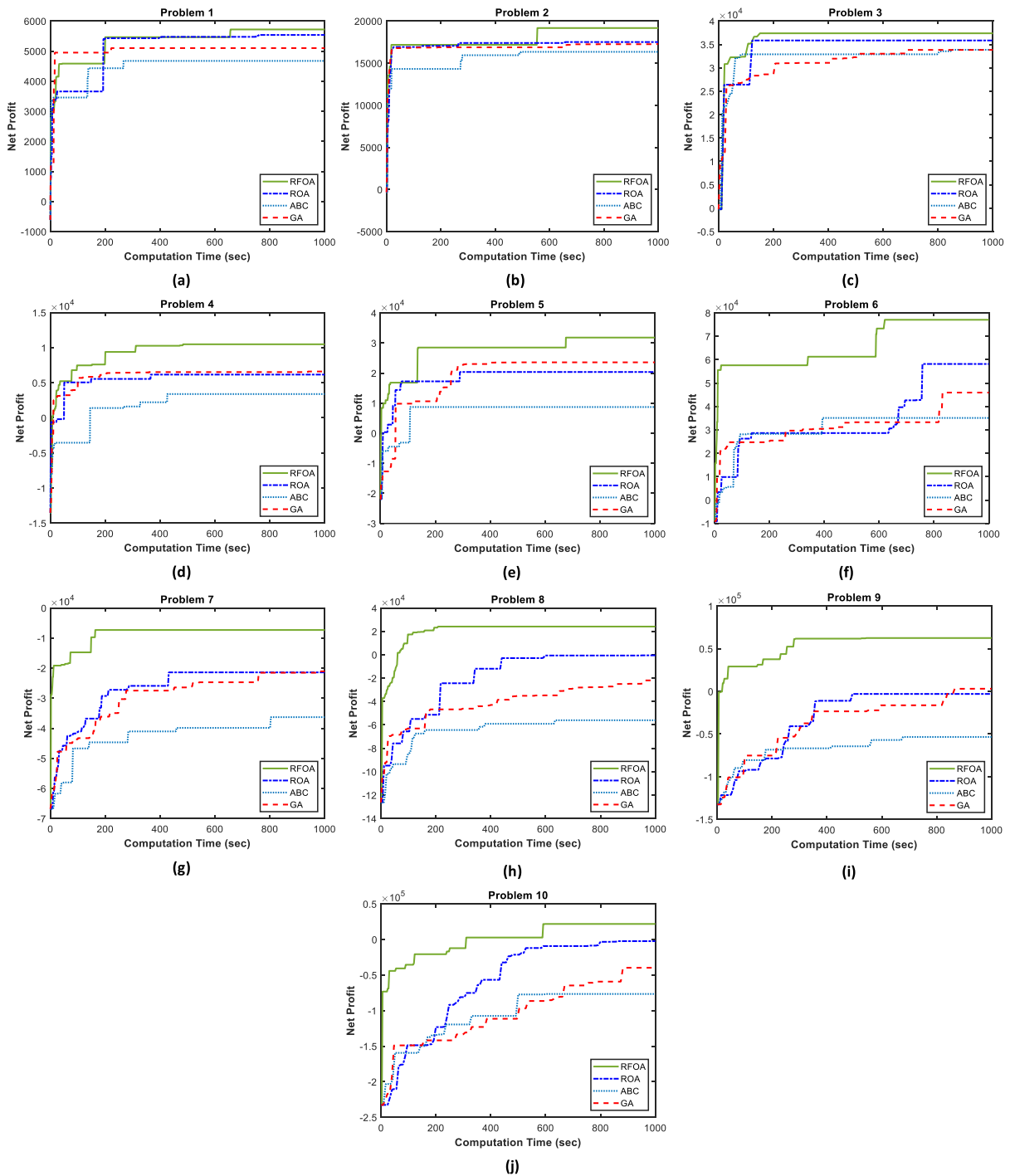


FIGURE 10. Convergence plots of algorithms for problem case instances.

are given in Figure 9. It can be seen from Figure 9 that the proposed RFO algorithm is statistically significant at the confidence interval of 95%. Further, the mean and median values of the objective function attained from the proposed RFO algorithm is significantly higher than the other compared algorithms. Moreover, the objective function values attained from the proposed RFO algorithm are close to each other

as compared to the other compared algorithm. Therefore, the robustness of the proposed RFO algorithm is higher than the other-mentioned algorithms. It can be concluded from the ANOVA analysis that the performance of the proposed algorithm RFO algorithm is significantly better and it provides more robust solutions as compared to the other algorithms.

TABLE 8. Characteristics of the project 4.

Activities	Successors	Modes	Process time
1	2, 6	1	0
2	3, 12	1	250
3	4	1	408
4	5	1	366
5	9	2	432
6	7	1	756
7	8	1	234
8	9	1	222
9	10	2	318
10	11	1	120
11	16	1	114
12	13, 14, 16	2	68
13	15	1	157
14	15	2	120
15	17	1	192
16	17	2	138
17	18	1	216
18	-	2	648
		1	165
		2	240
		1	420
		1	0

The convergence of the algorithms is as essential as the quality of the solution obtained. A good algorithm must have the ability to provide the optimum solution in the least computational time. Therefore, the convergence rate of the proposed RFO algorithm is compared with other algorithms mentioned above. Convergence plots of the algorithms for each problem case instance are given in Figure 10 (a) to Figure 10 (j). It can be seen from Figure 10 that the convergence rate of the proposed RFO algorithm is relatively high as compared to the other algorithms mentioned above. It can quickly converge as compared to the other algorithms without being entrapped into a local optimum solution. Problem 1 is the only case in which the convergence rate of GA was initially high, but it got trapped into a local optimum solution and did not improve further. However, the objective function value of the proposed RFO algorithm is better than that of the GA after 198 sec, as shown in Figure 10 (a). Thus, it can be concluded that the proposed RFO algorithm performs better as compared to other algorithms based on convergence analysis.

V. CASE STUDY

The current integrated planning and scheduling problem of multiple projects with different release date and execution modes is based on a project of advanced planning and scheduling system (APS) project for a well-known die and mould manufacturing company in China. Both die and mould manufacturing process consists of various activities such as heat treatment, grinding, milling, turning, drilling, punching and stamping. Available capacities of renewable and non-renewable resources are given in Table 4. The characteristics of the projects for a specific planning horizon are given in Table 5 to 8. It can be seen from Table 5 to 8 that there is a total

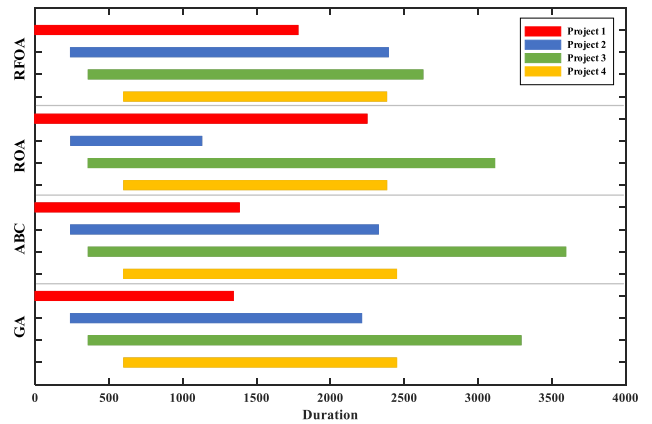


FIGURE 11. Gantt chart of optimum schedules.

of four projects having different numbers of activities that need to be scheduled. Previously in the test case instances, the number of modes available and renewable resources required per unit time for all activities are the same while, in real life, the number of modes available and renewable resources required per unit time for each activity can be different.

The proposed RFO algorithm for integrated planning and scheduling problem of multiple projects with different release date and execution modes is employed to help die and mould manufacturing company to formulate the detailed projects' plan with the optimal schedule which maximizes net profit. The proposed RFO and other compared algorithms are implemented on the case problem and the Gantt chart of optimum schedules obtained by various algorithms is given in Figure 11. Moreover, the net profit value of the schedules obtained from the proposed RFO, ROA, ABC, and GA algorithm is 14797.79 RMB, 8910.71 RMB, 6718.932 RMB and 6983.50 RMB respectively. It can be seen from figure 11 that the proposed RFO algorithm provided a better schedule with maximum net profit value as compared to the other algorithms. It can be concluded that the RFO algorithm provides better results and can help the project manager to make better scientific decisions on integrated planning and scheduling problem of multiple projects.

VI. CONCLUSION

In this work, integrated planning and scheduling problem of multiple projects with different release date and execution modes is investigated. Multiple projects and activities scheduling problems along with the mode assignment problem is solved to maximize the net profit while considering the early completion bonus, penalty cost and total resource cost. The introduction of renewable and non-renewable resource capacity constraints based on real-life scenarios increases the complexity of the current problem. Therefore, a novel RFO algorithm based on the social hierarchy and foraging behaviour of raccoons is proposed to solve the integrated planning and scheduling problem of multiple projects.

Further, greedy search and modified genetic operators are introduced for better exploration as well as exploitation. The Taguchi method along with the orthogonal arrays is used for the fine-tuning of the parameters of the algorithms. In order to validate the performance of the RFO algorithm, case study problem and test case instances are used. The performance of the proposed RFO algorithm is compared with the GA, ROA and ABC algorithms based on ARPD values, convergence, ANOVA analysis and robustness. It can be concluded from the experimental results that the proposed RFO algorithm performed significantly better as compared to the other algorithms mentioned above for integrated planning and scheduling problem of multiple projects.

This research can be extended to find the trade-off among multiple objectives (such as quality, time and cost triangle) and by introducing doubly resource constraints along with resource transfer time and cost. Additionally, for much better application on the real-world problems, scheduling policies and the theory of constraint tools such as critical chain project management can be integrated with the proposed RFO algorithm to form a hyper-heuristic algorithm with the capability to cope with the real-life uncertainties.

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