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A Multi-objective Resource-constrained Project Scheduling Problem Using Genetic Algorithm

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Keywords:
Multi- Objective, Resource-Constrained, Project Scheduling Problem, Genetic Algorithm, Precedence relations.

A B S T R A C T

Resource-Constrained Project Scheduling Problem (RCPSP) has been modeled as a single or multi-objectives, using minimization of project make-span, lateness, total weighted start time, total project cost and maximization of project net present value. In this paper, a multi-objective RCPSP incorporated resource idleness into the list of RCPSP objectives. Here, the RCPSP is modeled as a Mixed Integer Non-Linear Programme to depict the various objective factors namely cost, time and resource idleness. Genetic algorithm (GA) meta-heuristic solution technique is used to promote solution diversity and determine the Pareto optimal for the multi-objective problem. The performance of the proposed RCPSP model was evaluated using a standard test problem that consist of 5 activities, 3 reusable resource types and a network diagram; a comprehensive computational experiment was performed and the results were analyzed with precedence relations considering the objectives as single objectives, bi-objectives and in combined form as multi-objectives simultaneously. The integration of resources idleness into the multi-objective policy gives more realistic result.

1. Introduction

Resource-constrained project scheduling problem (RCPSP) remains a challenge to project managers in contemporary manufacturing, production planning, project design and the like; it has continued to attract a growing attention from researchers and project management experts, searching for enhanced solution techniques (Koulinas et al. 2014; F. Habibi e*t al*., 2018). RCPSP involves non-preemptive scheduling of project activities so that either the lead lag precedence relationships or resource constraints is not violated for optimal cost and time considerations. Hence RCPSP is NP-hard. A number of optimization techniques have been developed for solving the RCPSP depending on scale of project instances (Salem and Hassine, 2015; Abdolshal, 2014). Previous researches on RCPSP have focused on the development of RCPSP variants based on the original RCPSP formulation such as multi-mode problem formulation in which activities can be performed in several ways (Messelis and De Causmaecker, 2014), single-mode, pre-emption and non-pre-emption of activities, with reusable and non-reusable resources, single objective and multi-objective, multi project in which resources can be shared among several projects (Ma *et al*., 2016) etc. The single objective variant is sufficiently explored in literature (Hartmann and Briskorn, 2010). However, many real-world decision making problems often compels a tradeoff among many design considerations that gives rise to a set of Pareto-optimal solutions (Choi *et al*., 2017). The exact procedure of seeking such a solution is known as multi-objective modeling (Martínez-Iranzo *et al*., 2009). The number of probable multi-objective formulations for the RCPSP is largely dependent on the choices made by project professionals hence, countless number of conflicting objectives have been reported (Al-Fawzan and Haouari, 2005) and objectives of critical concern to

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decision managers and researchers, include the following: minimization of the project makespan; earliness or lateness; total project costs, resources availability costs; minimization of the total weighted start time of the activities; minimization of the number of tardy activities and maximization of the project net present value (Ballestín and Blanco, 2015).

Early research work on multiple objective RCPSP were premised on exact solution techniques as presented in (Blazewicz *et al*., 1983; Mohring *et al*., 2003; Mejia *et al*., 2017). The RCPSP was modeled as linear goal programming (LGP) model. Wieters (1979) presented an Integer Goal Programming (IGP) formulation to address multiple project scheduling problems competing for the same resources (i.e. renewable and non-renewable resources). In a related work, Slowinski (1989) presented a specialized optimization procedure for the multiple objective RCPSP, the algorithm creates all non-empty and different resource feasible subsets which do not violate the resource constraints. Both one-stage and two-stage multi objective linear programming (MOLP) methods were used to solve the problem. Palacio and Larrea (2016) formulated the RCPSP as a two Mixed-Integer Programming problem and used the exact solution technique to determine the optimal schedule. The first model was to minimize completion time of project, while the second maximizes the scheduling robustness. Several variants of the exact technique to RCPSP exist till date (Brucker *et al*., 1999; Kolisch and Padman 2001). However, the exact approach can only solve small scale problem instances in a satisfactory manner (Zhu *et al.*, 2006). Also, the exact algorithm requires several computations and as a result, they are slow to converge. Therefore, heuristic and metaheuristic solution procedures remain the only feasible way to obtain near optimal solutions for practically large resource-constrained project scheduling problems (Koulinas *et al*., 2014). Due to the computational complexity of the RCPSP, according to Thomas and Salhi (1998), the metaheuristic methods perform best in solving the resource constraint problem. Instead of whole space problem solution, a part of it is searched such that a good approximate solution is obtained at reasonable exponential time.

Several metaheuristic approaches have been reportedly developed to solve the RCPSP (Van Petegham and Vanhoucke, 2014). These include the Tabu Search (Yagiura and Ibaraki, 2001), the Pareto Simulated Annealing (PSA), the Genetic Algorithm (GA) (Mendes *et al*., 2009; Afshar-Nadjafi et al., 2013; Xhu *et al.*, 2017), Ant Colony Optimization (Li and Zhang, 2013) and hybrid algorithms (Myszkowski *et al*., 2015). Due to the successes recorded on the use of metaheuristics methods, the multi objective RCPSP formulation in this study will be solved using Genetic Algorithm (GA).

In this paper, a multi-objective RCPSP with synchronized conflicting objectives of Make-span, Total Cost and Resource Idleness minimization is proposed for the first time. The modeling technique is premised on hybrid of exact and meta-heuristic approaches.

2. The Model

2.1 Problem Description

A model was formulated for the RCPSP. The model consists of three objectives which made the RCPSP multi-objective in nature. The objectives are to minimize the project cost, project duration and resource idleness. The following assumptions were made in the development of the model: (1) Preemptive activities: once an activity is ongoing, it cannot be interrupted (2) Reusable resources: The resource types are reusable after a prior use (3) The project was funded via loan at some interest rate. (4) Deterministic approach is used.

2.2 Model Development

Let G = (V, A) represent a direct acyclic graph (project scheduling is usually represented by a direct acyclic graph), where the set of nodes V = {1, 2,…, n+1} represents activities in the project and the set of arcs (i, j) ∊ A with precedence link between activities

Let $G = (V, A)$ represent a direct acyclic graph (project scheduling is usually represented by a direct acyclic graph), where the set of nodes $V = \{1, 2, ..., n+1\}$ represents activities in the project and the set of arcs (i, j) □ A with precedence link between activities i and j such that,

$$f_{ij} = \begin{cases} 1 & \text{if activity } i \text{ immediately precedes } j,\ i \neq j \\ 0 & \text{otherwise} \end{cases}$$

So, if C_{i0} is the initial cost, x_i the start time and t_i, the duration of execution of activity i of the project, $i = 1, 2, \ldots, n$ and let r be the uniform compound interest rate of loan and $\overline{T}_s$ the cumulative time horizon of the loan procured up to the beginning of the current activity (T_s) at time segment s, $s = 1, 2, \ldots, S$ the actual cost of executing the activity is,

$$\overline{C_i} = f_{ij} C_{i0} (1 + r)^{[(\overline{T}_s + T_s - x_i)]}$$

Similarly, if $\theta(q)$ is the quantity of resource type q available for project execution, $q = 1, 2, \ldots, Q$ and defining two binary parameters,

$$R(i, q) = \begin{cases} 1 & \text{if activity } i \text{ uses resource type } q \\ 0 & \text{otherwise} \end{cases}$$

$$P(i, j) = \begin{cases} 1 & \text{if } i \text{ is an immediate predecessor of } j,\ i \neq j \\ 0 & \text{otherwise} \end{cases}$$

the resource idleness function of the model can be modeled as,

$$\sum_{q=1}^{Q} \{ \theta(q) x_n - \sum_{i=1}^{n} [R(i, q) t_i N(i, q)] \}$$

The first component term, $\theta(q)x_n$ of the function is the total amount of time that the totality of resource type q is available while the second time, $[R(i,q)t_iN(i,q)]$ is the amount of time for which resource type q for activity i which needs $N(i,q)$ number of the resource type will be engaged for the activity.

A number of constraints are also expedient to be developed for the problem on hand to be applied to influence all or some of the objectives. The Multi-Objective Resource Constrained Non-Linear Mixed Integer Mathematical Programme developed with respect to the problem on hand is thus:

$$\text{Min. } C = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} f_{ij} c_{i0} (1+r)^{[(\overline{T}_s + T_s - x_i)} \quad (1)$$

$$\text{Min. } x_{n+1} = x_n + t_n \quad (2)$$

$$\text{Min.} \sum_{q=1}^{Q} \{ \theta(q)x_n - \sum_{i=1}^{n} [R(i,q)t_i N(i,q)] \} \quad (3)$$

Subject to:
Constraints

$$\sum_{i=1}^{n} R(i,q)(x_i + t_i)N(i,q) \le \theta(q) \quad \text{for each q, } q = 1,2,\ldots,Q \quad (4)$$

$$P(i,j)[x_i + t_i - x_j] \le 0 \quad \text{for each pair of } (i,j),\ i,j = 1,2,\ldots,n \text{ and } i \ne j \quad (5)$$

Equation (1) is the Objective to minimize the total project cost. The total project cost is the total amount including interest rate on loans procured in order to execute the entire project.
Equation (2) is the Objective to minimize project Makespan, x_{n+1} where x_{n+1} is the is the start time of the dummy activity called 'Completion' which has a time duration, t_{n+1} = 0 (2) and which translates to the sum of the start time of the last activity x_n and and its duration of t_n.

Equation (3) is the Objective to minimize resource idleness representing the sum total of time for which resources of all types are not in use. Minimizing resource idleness has a huge positive effect in the overall optimization of an entire project.
Equation (4) are constraints on resource utilization. They ensure that resources of particular types and for particular activities do not exceed the maximum available of the type.
Equation (5) are precedence constraints ensuring that an activities are scheduled only if their immediate predecessors have been scheduled, these constraints make sure that the order required for scheduling activities is maintained.

1.1 Model Decision Variables

The decision variables in the RCPSP are the x_i's which are the start times of the activities in the given projects. By default the start time of the first activity or task is 0. The values of the start times of the other activities are then determined after solving the model.

1.1 Test Problem

In this work, a test problem that consists of 5 activities, 3 reusable resource types were considered. The network diagram, using Activity on Node (AON) convention and showing precedence relationship is represented in Figure 1. The duration, cost and resource requirement parameters of the model as enunciated in Section 3.2 are depicted in Tables 1. The maximum available units of resource types 1, 2, and 3 are respectively 7, 6 and 5. The test problem considers only one segment of loan procurement for project execution.

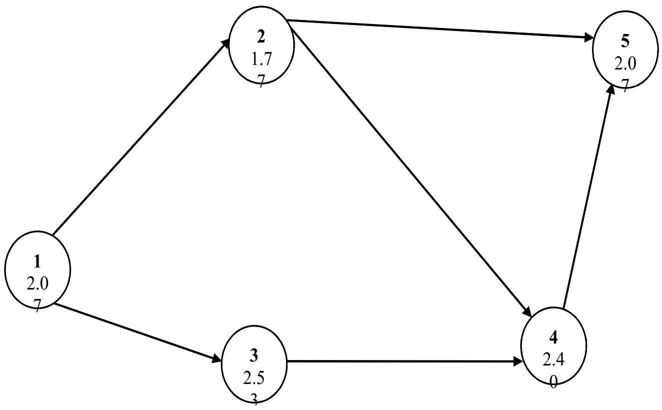

Figure 1: Network Diagram for the Test Problem

Table : Problem Activity Parameters

Activity	Duration (months)	Cost Parameters		Resource Type		
		Cost (In Thousands of Naira)	Interest Rate	1 (R1) (7)	2 (R2) (6)	3 (R3) (5)
1	2.07	221	0.02	3	4	2
2	1.77	895	0.06	2	1	3
3	2.53	494	0.04	4	1	2
4	2.40	396	0.04	5	2	3
5	2.73	634	0.06	3	1	2

$$\theta = \sum_{q=1}^{Q} \theta(q) = R1^{max} + R2^{max} + R3^{max} = 7 + 6 + 5 = 18 units \quad (6)$$

2.5 Solution Technique

Given the formulation of the model in Section 3.2, Genetic Algorithm (GA) solver in the Optimization Tool box in MATLAB (Matrix Laboratory) was used to solve the RCPSP. Crossover probability of 0.9 and mutation probability of 0.2 were used as GA parameters with no elitism in the selection mechanism.

In order to comprehensively investigate the variations in schedules and costs due to one or more of the three objectives, the model was solved using all possible combinations of the objectives under seven scenarios: (1) Total Cost Only, (2) Resource Idleness only (3) Makespan only (4) Total Cost plus Resource Idleness (5) Total cost plus Makespan (6) Makespan and Resource Idleness (7) All Objectives: Total Cost, Resource Idleness and Makespan. In order to compare different values of combinations of objective functions, with unit disparity and high value discrepancies, a normalization scheme was used so that all objective can be compared on equal pedestal in the interval [0 1]. Using the optimal values of the objective functions obtained for the first three scenarios, the ratios of the absolute deviations of individual values of the objectives obtained in the combinations in scenarios 4 to 7 from the corresponding adjudged optimal in the single objective scenarios 1 to 3 and the optimal values are computed to obtain normalized values. Thus for scenarios 4 to 7 with combinations of objectives with unit disparity and high objective value discrepancies where there are unit parities, the normalized combined objective value for scenarios 4 to 7 are obtained as:

$$\overline{O}_k = \left(1 - \frac{1}{n_k}\sum_{m=1}^{3}\frac{f_{mk}\left|O_m - \underline{O}_m\right|}{O_m}\right) \quad ; for\ each\ k = 4,5,6,7 \qquad (7)$$

where,

$\overline{O}_k$ $(O_m, \underline{O}_m)$ are the kth normalized objective value (Single Objective optimal value for scenario m, the current value of objective m contribution to the kth scenario), $m = 1, 2, 3$ and $k = 4, 5, 6, 7$. n_k is the number objectives combined in the kth scenario and

$$f_{mk} = \begin{cases} 1\ if\ the\ objective\ is\ part\ of\ combined \\ \quad objectives\ in\ the\ kth\ scenario \\ \quad otherwise\ zero \end{cases}$$

3.0 Results and Analysis

3.1 Results

The results obtained from solving the RCPSP model featuring the scheduled activity start times and optimal objective values for scenarios 1 to 3 and normalized objective values for scenarios 4 to 7 are presented in **Tables 2** and **3** below.

Table 2: Optimal Project Schedules in All Scenarios

Scenario		Activity Schedule (Start Times)					Project
No	Description	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Duration
1	Total Costs only	0.0010	3.8400	6.24	8.7692	11.5	**14.23**
2	Makespan only)	0.0000	2.0700	3.8400	6.3700	8.77	**11.50**
3	Resource Idleness only	0.0000	2.0700	3.8400	6.3700	8.77	**11.50**
4	Cost + Makespan	0.0000	2.0725	3.8400	6.3701	11.5	**14.23**
5	Cost + Resource Idleness	0.0000	2.0700	3.8400	6.3700	11.5	**14.23**
6	Makespan + Resource Idleness	0.0000	2.0700	3.8400	6.3700	8.77	**11.50**
7	All Objectives	0.0000	2.0700	3.8400	6.3700	11.5	**14.23**

Table 3: Optimal and Normalized Optimal Objective Values across All Scenarios

		Objective Values			
Scenario		Optimal			Normalized Optimal
No	Description	1 (×₦′)	2 (months)	3 (months)	
1	Total Costs only	2677.0			
2	Makespan only		11.5000		
3	Resource Idleness only			3.4542	
4	Cost + Makespan	2695.3	14.2300		0.877886
5	Cost + Resource Idleness	2695.3		4.7474	0.809390
6	Makespan + Resource Idleness		14.4686	3.9130	0.804519
7	All Objectives	2695.3	14.2300	4.7474	0.793795

3.2 Analysis

3.2.1 The Schedules

The schedules, as presented in Table 3, are compared pairwise using Chi-Square Test function, CHISQ.TEST of the Excel workbook for which the row identity is taken as the observed schedule values and the columns the expected schedule values, as presented in Table 4. For example, the correlation value for Scenario 3 (as the observed schedule values) and the Scenario 1 (as the expected schedule values) is 0.467739 as opposed for the case when the schedules are swapped giving a correlation value of 0.247302. An example of the graphical illustration of correlation value is presented in **Figure 2** (i.e. all Scenarios against Scenario 1).

Table 4: Chi-Square Pairwise Test of Independence of Schedules

	1	2	3	4	5	6	7
1	1	0.247302	0.247302	0.418194	0.417339	0.247302	0.417339
2	0.467739	1	1	0.882715	0.882715	1	0.882715
3	0.467739	1	1	0.882715	0.882715	1	0.882715
4	0.663895	0.827014	0.827014	1	1	0.827014	1
5	0.663469	0.827014	0.827014	1	1	0.827014	1
6	0.467739	1	1	0.882715	0.882715	1	0.882715
7	0.663469	0.827014	0.827014	1	1	0.827014	1

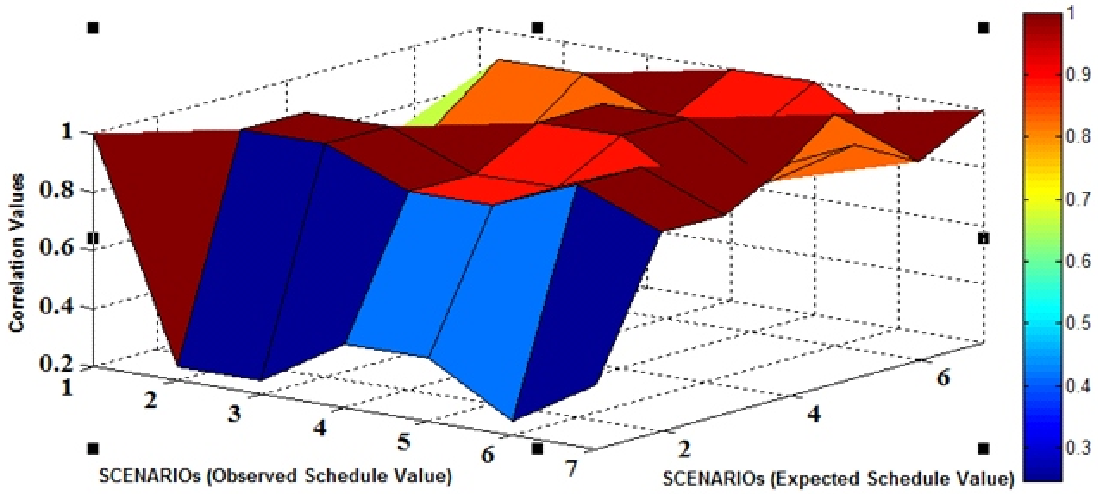

Figure 2: Pairwise Correlation Variations among the Optimal Objective Values

Compared to the multi-objective cases (scenarios 4, 5, 6, and 7), taken as expected values, the correlation schedule values for the first objective based on the total costs function, alone (scenario 1), taken as observed values, are quite low (0.418194, 0.417339, 0.247302 and 0.417339 respectively), an indication of distinct schedules pairwise. The same comparatively low comparisons can be observed for when the multi-objective cases are taken as observed values and the Single Objective (scenario 1) schedule values are taken as the expected values giving correlation values of (0.663895, 0.663469, 0.467739 and 0.663469 respectively). Thus the multi-objectivity of the influences scheduling appreciably compared with costs alone.

Compared with Single Objective Schedules 2 and 3 (Scenarios 2 and 3), the schedule distinctions from the multi-objective cases (Scenarios 4, 5, 6 and 7) are marginal and not as produced by the comparison with the Objective 1 (Scenario 1) schedules alone giving correlation values of (0.882715, 0.882715, 1, 0.882715 respectively) for both scenarios when the multi-objective cases (Scenarios 4, 5, 6, and 7) schedules are taken the expected values and (0.827014, 0.827014, 1, 0.827014 respectively) when they are taken as observed values.

Within the multi-objective schedules (Scenarios 4, 5, 6, and 7), there are marginal distinctions between schedule pairs when they are considered either as observed or expected values, the lowest correlation value among schedule pairs being 0.827014. This may not entirely prove high correlation among the multi-objectives cases of the model but occasioned by the test problem used.

In all, the justification for the use of multi-objective functions is evident.

4.2.2 Project Completion Times

Table 6 below depicts the completion times for each scenario. The multi-objective cases (Scenarios 4, 5, 6 and 7) compare equally well and better (in some cases) with the single objective (Scenarios 1, 2, and 3). In particular, the Scenario 6 combination, the bi-objective case (based on Makespan and Resource Idleness). This is an additional justification for multi-objective project scheduling.

Table 6: Project Completion Times for Different Objective Combination Scenarios

	Completion Times for Objective Combination Scenarios						
Scenario	1	2	3	4	5	6	7
Completion Time (months)	14.23	11.5	11.5	14.23	14.23	11.5	14.23

A graphical illustration of project completion times for different Objective combination of Scenarios is presented in **Figure 3**.

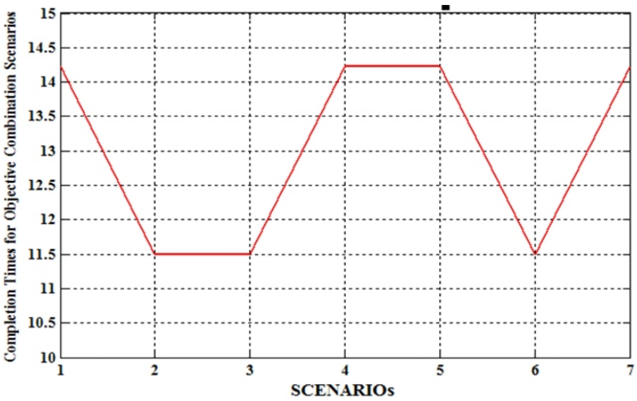

Figure 3: Project Completion Times for Different Objective Combination of Scenarios

3.2.3 The Objective Values

The analysis of the greatest lower bound of the objective function over the entire feasible region for multi-objective cases (Scenarios 4, 5, 6 and 7) is discussed in this section. **Table 7** and **Figure 4** show the normalized optimal objective value for various multi-objective Scenarios.

Table 7: Normalized Optimal Objective Values for Scenarios

	Normalized Optimal values			
Scenario	4	5	6	7
Normalized Optimal Objective Value	0.877886	0.80939	0.804519	0.793795

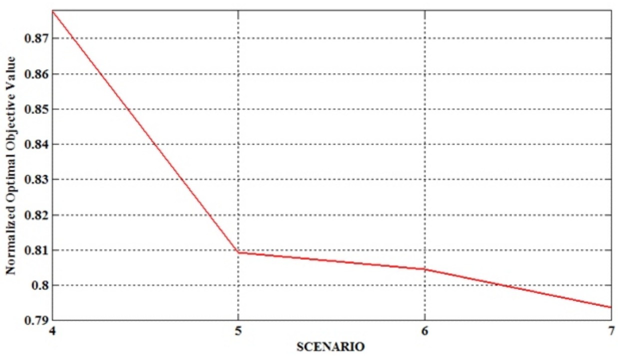

Figure 4: Normalized Optimal Objective Values for Scenarios

From **Figure 4**, the contributions of the individual objectives of the model to combined objectives are relatively higher than when the objectives were individually combined. This lends credence to the efficacy of multi-objective approach to problem solving for which broader interests are considered and each objective contribute to the optimal model solution. For example, optimal single objective values for consideration of Cost, Makespan and Resource Idleness alone are respectively ₦2, 677, 000.00, 11.5 months and 3.4542 months compared to ₦2,695, 300, 14.23 months and 4.7474 months of contributions made in the All Objectives case. Since the problem is a minimization problem, the All Objectives values are somewhat individually superior to the Single Objective values. The broader the interests to satisfy, the more the competition to contribute. The strength of multi-objectivity, in terms of synergy, however comes to play in the four scenarios of combinations as the All Objectives (Scenario 7) resulted in the least optimal normalized objective value of 0.793795 compared 0.877886, 0.809390 and 0.804519 for Scenarios 4, 5, and 6 respectively.

3.2.4 Resource Idleness in Focus

In particular, the resource idleness objective is worth elaborating on, as it there is scarce attention to its effect on project scheduling in literature.

Table 8: Project Resource Idleness across Scenarios

	Resource Idleness for Scenarios			
Scenario	3	5	6	7
Resource Idleness (months)	3.4542	4.7474	3.913	4.7474

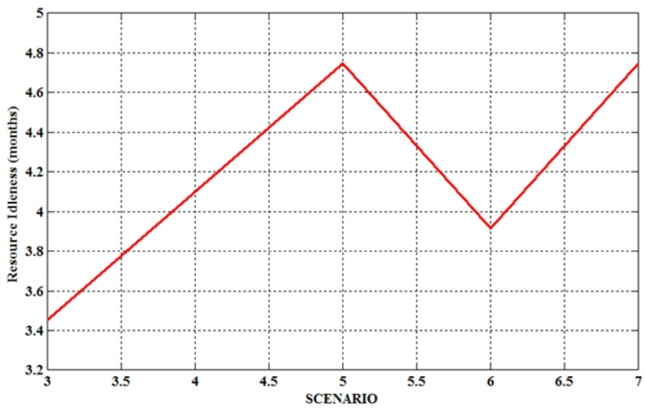

Figure 5: Project Resource Idleness across Scenarios

Minimizing resource idleness contributed positively to multiple objective optimal value reduction as evident in Tables 4 and 8. Compared to the multi-objective case of combining Costs and Makespan resulting in normalized optimal value of 0.877886 the contribution of resource idleness to Makespan in Scenario 5 gives a normalized optimal value of 0.804519 and resource idleness to costs at 0.809390, and resource with both Makespan and Costs of

0.793795. From Table 8 there are marginal increases of 1.2932, 0.4588 and 1.2932 months in the contributions of resource idleness in Scenarios 5, 6, and 7 multi-objective cases in which it is involved. These gives credence to positive contributions of resource idleness in multi-objective project scheduling.

4.0 Conclusions

This work has integrated total project costs, makespan and resource idleness as objectives in solving Resource-Constrained Project Scheduling Problem (RCPSP). A Mixed Integer Non-Linear Mathematical Programming model was built for that purpose. The test model results justify the incorporation of multi-objectivity in project scheduling, particularly the inclusion of project resource idleness minimization whose inclusion is sparse in literature.

4.1 Extensions

To determine the lower and upper bounds of activity project duration, rather than time-based technique, other method of determination of these bounds can be looked into, e.g. resource-based technique may be considered. The Multi-mode approach can also be used while solving the problem using test problem. Algorithms can be developed to solve each objective differently. Also to solve the several objectives as a multi objective problem, algorithms can also be developed for multi-project problem. These algorithms developed can be extended in such a way that it can accommodate aspects like delay of resources, weather condition etc. Models that can accommodate pre-emptive activities can be formulated for the MRCPSP. Moreover, models that can accept non reusable resources or both reusable and non-reusable resources for a project can also be looked into.

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