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A Mathematical and Heuristic Approach for Scheduling Repetitive Projects in a Bi-Objective Single Crew Model

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Projects in which same type of works/activities gets repeated in different locations or sites are known as repetitive projects. In repetitive project businesses, selecting the best choice from distinctive crew options for each activity is a very difficult task for the decision makers. To find an optimum schedule with respect to different objectives like total project cost, total project duration etc. is of utmost importance for any project industry. In this study we consider a single crew model and develop a mathematical model which can give optimal solutions to the various objectives considered here, by satisfying different constraints like the work continuity of different resources in different units, fine amount to the lagging day of each activity in every location and precedence activities of the project. The proposed model is applied using a solver and validated by using complete enumeration technique. As in the case of any computationally complex problem, for problems of large size, a heuristic methodology is essential to obtain a good schedule, as solving of mathematical model is computationally difficult. So, here we also propose a new heuristic based methodology named as IGA-SCRP (Improved Genetic Algorithm for Single Crew Repetitive Projects). It is a modified genetic algorithm based methodology and its performance is compared with solutions acquired from the mathematical model. The outcome from the results shows that the proposed heuristic gives quality of solutions with minimal computational effort.

Keywords: Complete enumeration technique, IGA-SCRP, Mathematical model, Genetic algorithm, Repetitive projects

Introduction

Linear projects or repetitive projects are projects involving repetitive activities. Different buildings in a housing project, runways in an airport, tunnels or bridges in different area, different sections in a pipeline construction, railway line construction etc. are considered as repetitive projects. However in practical situations, different site locations/ units may not be the same in many repetitive projects. For example, the number of nozzles and the length of different pipe sections will not usually equivalent in different segments of a pipeline project; the shape and size of each storage vessel may be different in a multi-storage vessel plant. Therefore the prescribed assignment of quantity of work and its expenditure and duration will be dissimilar in different segments. A single crew model in a repetitive project is one in which the selected crew of each activity moves along different units (locations) to execute the same work of that activity. For example, a foundation crew will do the same work again in different locations (units) in the construction of a building. But To manage crew work continuity is most important for a construction company, for which different units must be scheduled in such a way as to allow the proper flow of crews from one location to another for avoiding the idle time of crew. So this ‘crew work continuity constraint’ has a major role for reducing the idle time of each crew, increasing the learning curve effect and control the flow of crew at the time of project. Preparing a proper schedule by satisfying the different functions in a project is very much important for project industry due to the stiff competition in this field and also the decision makers of a project would want to do the selection of specific crew from different alternative options available in a shorter time period.

Literature Review

The main practical requirement of scheduling repetitive project is the ability to optimize one or more objectives such as minimize project duration[1,2], minimize project cost[3–5], or maximize NPV[6,7] etc. Bi-objective optimization is the operation of collectively optimizing two conflicting objectives subject to various constraints. In repetitive project works,

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simultaneously optimizing two different objectives like minimize duration and cost, minimize duration and interruption days etc. is most important. It is seen from the literature that there are only a few articles that focus on bi-objective optimization.[8–10]

From the literature review, it can be easily understood that the scheduling of repetitive projects, wherein activities repeat from unit to unit, represents a major challenge to the project managers. These projects need continuous utilization of an activity in one location to the similar activity in the next location while maintaining precedence relationship at the same time. The main interest of this study is to develop a method for finding out an effective schedule for repetitive project works that helps in minimizing the cost and duration of the project by dealing with various limitations like precedence relationships between activities, resource work continuity and the delay cost corresponding to the lagging activity. Some of the project industries are following a single crew model in which they select a particular crew/resource for each activity and it moves along different project sites to complete the work. Based on this, the present study looks at developing a mathematical model for optimally scheduling a repetitive project problem in a single crew model. This study also proposes a heuristic based methodology for solving large size repetitive project scheduling problems. The method looks at a trade-off between decision quality and computational speed and portrays a comparative picture of the proposed methods.

Model Description

A project industry is performing same type of works in ‘L’ particular locations (units) and each unit is branched into ‘K’ different activities.[11] These activities have some precedence relationship and these are continuing from one location to other. Here a single crew model is considered in which a crew corresponding to different activities are moved within different locations. A particular crew is selected from the multiple crew options available on each activity and every crew has a separate expenditure and duration per unit amount of work. The model is designed to find the optimum schedule in three scenarios comprising of total project duration, total project expenditure and a bi-objective optimization of minimize the combined effect of both duration and expenditure.

Assumptions

The following assumptions are made to solve this problem.

Quantity of work of activity

The amounts of work of individual activities are distinct in different locations.

Duration per Unit Quantity of Work

As mentioned earlier, each crew has an independent duration per unit quantity of work and total duration is found out by multiplying duration per unit quantity of work with quantity of work.

Direct Cost per Unit Quantity of Work

A particular crew has a specific cost per unit quantity of work and direct cost is the product of direct cost per unit amount of work and quantity of work.

Lateness Penalty Cost

If an activity is delayed due to any reason from its delivery date, then corresponding project industry should pay a fine amount to the customer corresponding to each lagging day.

Mathematical formulation

Luong *et al.* (2009) proposed a mathematical model to solve a repetitive project scheduling problem for minimizing the total duration and expenditure of the project and minimize the combined effect of both with respect to different constraints like precedence relationship between activities and resource work continuity.[8] In the present problem, we also consider the penalty cost corresponding to each activity in every lagging project as well. The model of Luong *et al*. (2009) is suitably modified to this extent.

$$x_{cm}\begin{cases} 1 & if\ c \text{ th crew of } m\text{th activity is assigned to any unit} \\ 0 & otherwise \end{cases}$$

Objectives

Objective 1: Minimize total project duration

$$T\_\text{min}=\text{Min}\{\text{Max}\textstyle\sum_{m=1}^{K}\sum_{n=1}^{L}\sum_{c=1}^{Q}x_{cm}\times\left(ST_{mn}+(d_{cm}\times qw_{mn})\right)\} \quad \ldots(1)$$

Objective 2: Minimize total project expenditure

$$E\_\text{min}=\text{Min}\Big(\Big(\textstyle\sum_{m=1}^{K}\sum_{n=1}^{L}\llbracket\big[\sum_{c=1}^{Q}x_{cm}\times(e_{cm}\times qw_{mn})+(LT_{mn}\times p_m)\big]\Big)+\Big(IC\times\text{Max}\sum_{m=1}^{K}\sum_{n=1}^{L}\sum_{c=1}^{Q}x_{cm}\times\big(ST_{mn}+(d_{cm}\times qw_{mn})\big)\Big)+E_o\rrbracket\Big) \quad \ldots(2)$$

Objective 3: Minimize combined effect of both project expenditure and project duration expenditure

$$DE = \sqrt{((w_d(((TD - T\_min)/T\_min)^2)) + (w_e(((E - E\_min)/E\_min)^2))} \quad \dots (3)$$

Constraints

1. Precedence relationship between different activities

$$\sum_{c=1}^{Q} x_{ki} \times (ST_{mn} + (d_{cm} \times qw_{mn})) \leq ST_{m'n}$$

m=1, 2…. K; n=1, 2……., L. ... (4)

2. Work continuity relationship in different units of each activity

$$x_{cm} \times (ST_{mn} + (d_{cm} \times qw_{mn})) \leq ST_{mn'}$$

3. *m=1, 2…, K; n=1, 2…….L; c=1, 2…Q* … (5)

Start –finish relationship of each activity in every site.

$$(ST_{mn} + (d_{cm} \times qw_{mn})) = FT_{mn}$$

m=1, 2…., K; n=1, 2……., L. ... (6)

4. Lateness time[9] of activity *m* in unit *n*

5. $\boldsymbol{LT_{mn}}$=Max (0, $\boldsymbol{FT_{mn}}$-$\boldsymbol{DT_{mn}}$) … (7)

Not more than one crew is assigned to each activity.

$\sum_{c=1}^{Q} x_{cm}$=1 *m=1, 2…, K* … (8)

Here Eqs 1 and 2 represent the objective functions of the single objective optimization of minimizing total project duration and minimizing total expenditure of the project. These objective functions are found out independently by satisfying the mentioned constraints; in this objective 1 mainly depends on the parameter duration per unit quantity of work (d_{cm}) while the objective 2 is mainly dependant on direct expenditure per unit quantity of work (e_{cm}). These two parameters are contradicting in nature where a particular crew has minimum d_{cm} then it's e_{cm} should be maximum. But here it is assumed that each crew has an independent d_{cm} and $e_{cm}$and it is deterministic in nature.

The third equation (objective 3) produces a bi-objective function (multi objective optimization) in which *DE* is a trade-off solution examining the minimum relative deviation from the optimum solutions which is obtained from the first two equations.[12] Here specified weights (in the range [0.0, 1.0]) are chosen by the project decision makers by analysing the proportionate significance of total duration of the project and total expenditure of the project where it should satisfy the relationship (w_d+w_e=1.0). Different constraints with respect to the above objective functions are represented by Eqs 4 to 8.

Solution Methodology

The model description corresponding to the single crew model for solving the repetitive project scheduling problem is shown in the previous section. This paper provides a dual approach for solving these problems. In first case, a mathematical programming model is used to find out the solutions and the advantage of this method is that it provides an optimal solution (optimum solutions corresponding to all the three objectives) but with its own limitations in terms of very high computational effort. Researchers have developed lot of heuristic methodologies for addressing different types of problems.[6–10,13,14] So here a heuristic is also proposed to address complex problems as they can deliver solutions for practically any run time with minimal computational effort.

Exact Method

IBM ILOG Cplex 12.5 optimizer is used to solve the problems for finding out the different objectives with respect to the corresponding constraints. Expenditure and duration per unit quantity of work of each activity in every unit, quantity of work of each activity in every unit, penalty cost corresponding to each activity, the due date in which each activity in every unit should complete, indirect cost per unit duration and original cost are the input parameters to the solver. The mathematical programming model was verified with the help of complete enumeration technique through which the complete schedule corresponding to a sample problem was generated for all possible scenarios.

IGA-SCRP methodology

The main disadvantage of using a solver based approach is the exponential increase in computational time as the problem size increases. Beyond a point the solver terminates citing execution limitations. For example a project in which 20 different activities and 5 different resource options for each activity create a search space of 95 trillion (i.e 5^{20}) possible solutions.[15]

Genetic algorithms (GAs) have been successfully used as a search and optimization tool in different areas including project scheduling. The success of GAs in these fields can be attributed to their broad applicability, in terms of their ability to handle various types of functions and constraints. This work proposes a modified Genetic Algorithm based methodology named IGA-SCRP (Improved Genetic Algorithm for Single Crew Repetitive Projects) for solving computationally intensive problems wherein exact solution techniques cannot be applied.

For validating the methodology, the heuristically generated solutions are compared with the results obtained from solving the mathematical formulation (for small problems) and also by using complete enumeration technique using excel software.

Generation of Chromosome and Population

Premature convergence is a major issue in genetic algorithm based methodology when solutions are produced. It is because of anyone of the chromosome in the population can be fit than any of its competitors. So this particular chromosome may reproduce many more offspring and due to this, the diversity of the new population reduces and the solution converges into a local optimum. One of the reason for this issue could be the inefficiency of the initial population. In the developing stage of a suitable solution methodology, we thought about various techniques that could improve the efficiency of the initial population of a genetic algorithm. Here a randomly created initial population is applied in which each individual chromosome composed of different genes which are arranged end by end. If a project consists of *K* activities, then each chromosome contains *K* genes. Decision variable corresponding to each gene is the duration per unit quantity of work of the corresponding activities and the chromosome representation is shown in Fig. 1 where d_{c1}, d_{c2},…..etc. represent the duration per unit quantity of work of activity 1, activity 2…….etc.

The fitness evaluation of each chromosome in the initial population is done by applying the Eq. 3 in which *TD* and *E* are the duration and expenditure of the individual chromosomes is looking for the minimum deviation from the value which has the minimum value of the mentioned parameters in the population. After fitness evaluation, each chromosome generates a new chromosome from its neighbourhood randomly by using Eq. 9.

$$GN_{ij}= G_{ij}+ rand[-1,1]\ X(G_{ij}- G_{kj}) \quad \text{... (9)}$$

Here gene of i^{th} chromosome of j^{th} position (G_{ij}) is replaced with GN_{ij} is an absolute value which is found out by the sum of the present value of the gene is added with a number in which a random number in between −1 to 1 is multiplied with a number with the difference between gene of i^{th} chromosome in j^{th} position and gene of k^{th} chromosome in j^{th} positon where *j* and *k* positions are fixed randomly. Then a greedy selection process is used to select the best one from the initial chromosome and the newly generated one. It will repeat in every chromosomes of the initial population.

Parameters Setting

The performance of GA is commonly sensitive to the setting of the parameters that influence the search behaviour and quality of convergence. In order to get good quality solutions, it is highly desirable to set these parameters to a particular level.

For tuning cross over rate and mutation rate, different values available in the literature were considered and after initial testing, the following parameters were selected for detailed analysis. The values were 0.8, 0.7 and 0.6 for cross over rate (cr) and 0.6, 0.5, 0.4, 0.3 and 0.2 for Mutation Rate (mr). A pilot study conducted using the modified GA with different combination of parameters is given in Table 1. The different solutions (minimum combined

d_{c1}	d_{c2}	d_{c3}	d_{c4}	d_{c5}	…………..	d_{cK}

Fig. 1 — Chromosome representation of IGA-SCRP

Table 1 — A Pilot study for fixing cross over rate and mutation rate in GA

Problem setting	mr=0.2			mr=0.3			mr=0.4			mr=0.5			mr=0.6		
	cr= 0.6	cr= 0.7	cr= 0.8	cr= 0.6	cr= 0.7	cr= 0.8	cr= 0.6	cr= 0.7	cr= 0.8	cr=0.6	cr= 0.7	cr= 0.8	cr= 0.6	cr= 0.7	cr= 0.8
PS1	0.122	0.171	0.106	0.110	0.191	0.147	0.146	0.130	0.060	0.106	0.109	0.113	0.078	0.151	0.121
PS2	0.111	0.134	0.137	0.114	0.097	0.085	0.111	0.110	0.139	0.131	0.111	0.093	0.078	0.100	0.166
PS3	0.140	0.139	0.169	0.181	0.163	0.086	0.105	0.101	0.067	0.119	0.090	0.108	0.183	0.143	0.098
PS4	0.168	0.106	0.150	0.126	0.095	0.138	0.093	0.067	0.067	0.084	0.082	0.068	0.125	0.107	0.079
PS5	0.145	0.133	0.110	0.117	0.092	0.138	0.093	0.073	0.108	0.089	0.086	0.068	0.175	0.102	0.082
Average	0.137	0.137	0.134	0.129	0.128	0.119	0.110	0.096	0.088	0.106	0.096	0.090	0.128	0.121	0.109

effect value of both duration and cost) corresponding to those parameters is shown in Table 2. From this a value of 0.8 was fixed for cross over operation and 0.4 for mutation operation.[16] Further, another pilot study was conducted to compare the static mutation rate (mr) of 0.4 (best value obtained from Table 1) with a dynamically varying mutation rate of 0.5, 0.4, etc., to 0.1 for generations less than 100, 100 to 250, 250 to 500, 500 to 1000 and more than 1000 respectively. This was applied in five different problem settings as shown in Table 2 with a fixed cross over rate of 0.8. We can see from the table that the performance of dynamically varying mutation rate is more effective than that of the static one.

Here population size is settled as a function of decision variable and it is fixed as four times the number of decision variables. Total number of generations is fixed as two times the population size. These parameter settings give near optimum solutions in most of the problems.

Table 2 — A Pilot study for fixing mutation rate in IGA-SCRP

Problem Setting	mr=0.4	mr=0.5 to mr=0.1
PS1	0.060	0.071
PS2	0.139	0.083
PS3	0.067	0.072
PS4	0.067	0.100
PS5	0.108	0.103
Average	0.088	0.086

Results and Discussion

Problem 1

Here, we analyse the concrete bridge example, in which the project has four similar units, and each unit have five different repetitive activities in sequence. Each repetitive activity is carried out by a crew that shifts from one location to others sequentially. The relationships among activities are finished to start. Different crew options corresponding to each activity and its duration and expenditure for unit quantity of work is taken from the literature as shown in Table 3.[(8)] As mentioned earlier, some modifications are given to the original problem in which the penalty cost corresponding to each activity is given in Table 4 and the due dates of each activity in every unit from the starting date is shown in Table 5. Here it is assumed that total cost is more dependent on the direct cost per unit amount of work of individual crew and therefore comparatively smaller values like an indirect cost of Rs. 25/day and an initial cost of Rs. 1000 are used in this example.

There are 72 feasible solutions possible in this problem. In each problem, five different pseudo random number sequences (seed numbers) are applied to generate initial feasible solution and other random variables for testing.[17] The results corresponding to the three objective functions using CPLEX solver and heuristic method are shown in Tables 6–8. This mathematical model is validated by complete enumeration technique and all the schedules

Table 3 — Input details for problem 1

Activity/ Unit	Quantity of work (m^2)				Crew option
	Unit 1	Unit 2	Unit 3	Unit 4	Duration/unit quantity(days) and Cost/unit quantity(Rs)
Excavation	600	750	520	800	{1/48,50}
Foundation	920	960	840	800	{1/80,80}, {1/64,70}, {1/48,60}
Columns	1450	1200	1800	1400	{1/80,70},{1/96,80}, {1/112,100}
Beams	480	520	570	450	{1/56,65},{1/48,70},{1/32,90},{1/40,80}{1/40,80}
Slabs	0	1140	940	1200	{1/72,55}, {1/64,65}

Table 4 — Penalty cost per unit duration (Rs/day) of each activity for problem 1

Activity	Excavation	Foundation	Columns	Beams	Slabs
Penalty	1	2	0	2	1

Table 5 — Deadlines (days) for each activity in every site for problem 1

Activity	Excavation	Foundation	Columns	Beams	Slabs
Unit 1	10	20	40	50	50
Unit 2	30	40	60	70	80
Unit 3	40	50	80	90	100
Unit 4	50	60	90	100	112

Table 6 — Results for objective 1 of problem 1

Seed	Methodology	Min. Duration	Cost	Schedule
Seed 1	IGA-SCRP	107	1316773	A1-B1-C2-D1-E1
Seed 2				
Seed 3				
Seed 4				
Seed 5				
	OPTIMUM	107	1316773	A1-B1-C2-D1-E1

Table 7 — Results for objective 2 of problem 1

Seed	Methodology	Min. Cost	Duration	Schedule
Seed 1	IGA-SCRP	1070544	134	A1-B3-C1-D1-E1
Seed 2				
Seed 3				
Seed 4				
Seed 5				
	OPTIMUM	1070544	134	A1-B3-C1-D1-E1

Table 8 — Results for objective 3 of problem 1

Seed	Methodology	Min. Combined effect	Duration	Cost	Schedule
Seed 1	IGA-SCRP	0.081	115	1163544	A1-B2-C2-D1-E1
Seed 2					
Seed 3					
Seed 4					
Seed 5					
	OPTIMUM	0.081	115	1163544	A1-B2-C2-D1-E1

(72 options) for problem1 is shown in Table 9 and the optimum results for the three objectives are the same as obtained from mathematical model solved with CPLEX solver. The heuristic method also gives the optimum solution in all the runs.

Bi-Objective Optimization

In this problem, different weights are assigned to both duration (w_t) and cost (w_c) to check the non-dominating solutions with respect to conflicting objectives by applying the methodology IGA-SCRP and it is shown in Table 10. From the solutions, we can see that the different solutions give smaller values of duration if more weightage is given to that parameter and vice versa. Problem 1 is a small size problem in which 72 possible solutions are there and therefore the same schedules are obtained in different combination of weightages. It is to be noted that the answers given are obtained by using a single seed value for comparison and representation purpose.

Problem2

Another problem of 18 activity, 5 unit problem is taken from the literature is also solved here using the methodologies.[9] There are 7.776×10^9 feasible solutions possible in this problem. For finding out the optimum schedule, the mathematical model is solved with IBM ILOG CPLEX 12.5 optimizer. Five different pseudo random number sequences (seed numbers-represented as Seed 1, Seed 2….Seed 5) are applied for testing this problem using IGA-SCRP based methodology and results of both methodologies corresponding to the three objective functions are given in Tables 11–13. In this problem we can see that the heuristic methodology give nearby answers in different random number sequences. The percentage deviations of heuristic methodology from optimal solution for the three objective functions are given in Table 14 and we can see that all the results are close to the optimum solution.

Percentage deviation of solutions obtained using IGA-SCRP from the optimum solutions with respect to three objective functions are given in Table 15. It is to be noted that average values obtained from the five random number streams are considered here for computing the percentage deviation. Here we can see that the average percentage deviation of IGA-SCRP is negligible from the optimum for the three objectives.

Bi-objective Optimization

As discussed in the previous test problem, different weights are assigned to both the objectives and are solved with different methodologies. Different solutions are generated from the search space and are shown in Table 15.

Table 9 — Complete schedule of Problem 1

Sl No	Crew option	Duration	Cost	Combined effect	Sl No	Crew option	Duration	Cost	Combined effect
1	1-1-1-1-1	122	1140400	0.109	37	1-1-1-1-2	124	1173257	0.131
2	1-2-1-1-1	125	1105326	0.121	38	1-2-1-1-2	127	1138185	0.140
3	1-3-1-1-1	134	1070544	0.178	39	1-3-1-1-2	136	1103409	0.193
4	1-1-2-1-1	111	1198603	0.089	40	1-1-2-1-2	115	1231502	0.119
5	1-2-2-1-1	115	1163544	0.081	41	1-2-2-1-2	119	1196455	0.115
6	1-3-2-1-1	128	1128848	0.144	42	1-3-2-1-2	132	1161752	0.176
7	1-1-3-1-1	107	1315498	0.162	43	1-1-3-1-2	111	1348412	0.185
8	1-2-3-1-1	113	1280483	0.144	44	1-2-3-1-2	117	1313384	0.173
9	1-3-3-1-1	126	1245756	0.171	45	1-3-3-1-2	129	1278660	0.200
10	1-1-1-2-1	123	1160645	0.121	46	1-1-1-2-2	125	1193505	0.144
11	1-2-1-2-1	126	1125594	0.131	47	1-2-1-2-2	128	1158454	0.150
12	1-3-1-2-1	136	1090800	0.192	48	1-3-1-2-2	138	1123661	0.208
13	1-1-2-2-1	476	1230639	2.441	49	1-1-2-2-2	478	1263498	2.455
14	1-2-2-2-1	479	1195592	2.460	50	1-2-2-2-2	481	1228452	2.474
15	1-3-2-2-1	484	1160647	2.492	51	1-3-2-2-2	486	1193507	2.506
16	1-1-3-2-1	108	1335740	0.175	52	1-1-3-2-2	113	1368651	0.201
17	1-2-3-2-1	115	1300728	0.161	53	1-2-3-2-2	118	1333630	0.188
18	1-3-3-2-1	127	1266016	0.185	54	1-3-3-2-2	131	1298920	0.219
19	1-1-1-3-1	128	1191131	0.160	55	1-1-1-3-2	131	1224006	0.188
20	1-2-1-3-1	131	1156084	0.168	56	1-2-1-3-2	134	1188959	0.195
21	1-3-1-3-1	141	1121290	0.227	57	1-3-1-3-2	143	1154166	0.244
22	1-1-2-3-1	120	1249356	0.146	58	1-1-2-3-2	122	1282232	0.171
23	1-2-2-3-1	124	1234342	0.156	59	1-2-2-3-2	127	1247217	0.176
24	1-3-2-3-1	137	1179656	0.211	60	1-3-2-3-2	140	1212532	0.237
25	1-1-3-3-1	117	1366261	0.206	61	1-1-3-3-2	119	1399136	0.231
26	1-2-3-3-1	122	1331251	0.199	62	1-2-3-3-2	124	1364127	0.224
27	1-3-3-3-1	134	1296567	0.233	63	1-3-3-3-2	137	1329443	0.262
28	1-1-1-4-1	125	1170814	0.136	64	1-1-1-4-2	127	1203678	0.159
29	1-2-1-4-1	128	1135767	0.145	65	1-2-1-4-2	130	1168631	0.165
30	1-3-1-4-1	137	1100973	0.199	66	1-3-1-4-2	140	1133837	0.222
31	1-1-2-4-1	115	1229012	0.117	67	1-1-2-4-2	119	1261915	0.149
32	1-2-2-4-1	119	1193977	0.114	68	1-2-2-4-2	123	1226881	0.148
33	1-3-2-4-1	132	1159294	0.175	69	1-3-2-4-2	136	1192198	0.208
34	1-1-3-4-1	111	1345900	0.184	70	1-1-3-4-2	115	1378809	0.210
35	1-2-3-4-1	117	1310899	0.172	71	1-2-3-4-2	121	1343803	0.203
36	1-3-3-4-1	130	1276204	0.204	72	1-3-3-4-2	133	1309108	0.233

Table 10 — Solution corresponding to bi objective optimization in problem 1 using IGA-SCRP

Weights	w_t=1, w_c=0	w_t=0.8, w_c=0.2	w_t=0.7, w_c=0.3	w_t=0.6, w_c=0.4	w_t=0.5, w_c=0.5	w_t=0.4, w_c=0.6	w_t=0.3, w_c=0.7	w_t=0.2, w_c=0.8	w_t=0, w_c=1
Duration (Days)	107	112	112	115	115	115	121	125	134
Cost (Rs)	1315498	1198600	1198600	1163544	1163544	1163544	1144315	1105300	1070544

Table 11 — Results for objective 1 of problem 2

Seed	Methodology	Min. Duration	Cost	Schedule
Seed 1	IGA-SCRP	69	131623	A1-B1-C1-D1-E1-F1-G1-H1-I1-J1-K1-L1-M1-N1-O1-P1-Q1-R1
Seed 2				
Seed 3				
Seed 4				
Seed 5				
OPTIMUM		69	131623	A1-B1-C1-D1-E1-F1-G1-H1-I1-J1-K1-L1-M1-N1-O1-P1-Q1-R1

Table 12 — Results for objective 2 of problem 2

Seed	Methodology	Min. Cost	Duration	Schedule
Seed 1	IGA-SCRP	122064	88	A1-B1-C2-D1-E5-F1-G1-H3-I3-J2-K3-L1-M1-N1-O1-P2-Q3-R1
Seed 2		122284	90	A1-B1-C1-D2-E5-F1-G1-H3-I3-J2-K3-L1-M1-N1-O1-P3-Q3-R1
Seed 3		121414	89	A1-B1-C1-D1-E5-F1-G1-H3-I5-J2-K3-L1-M1-N1-O1-P2-Q3-R1
Seed 4		121184	86	A1-B1-C1-D1-E5-F1-G1-H3-I3-J2-K3-L1-M1-N1-O1-P3-Q3-R1
Seed 5		121984	86	A1-B1-C1-D1-E5-F1-G1-H3-I3-J2-K2-L1-M1-N1-O1-P3-Q3-R1
OPTIMUM		120089.5	87	A1-B1-C1-D1-E5-F1-G1-H2-I5-J2-K3-L1-M1-N1-O2-P3-Q3-R1

Table 13 — Results for objective 3 of problem 2

Seed	Methodology	Min. Combined effect	Duration	Cost	Schedule
Seed 1 Seed 5	IGA-SCRP	0.0499	71	128723	A1-B1-C1-D1-E1-F1-G1-H1-I1-J1-K1-L1-M1-N1-O1-P1-Q2-R1
Seed 2 Seed 3 Seed 4		0.0482	72	127273	A1-B1-C1-D1-E1-F1-G1-H1-I1-J1-K1-L1-M1-N1-O1-P1-Q3-R1
OPTIMUM		0.0482	72	127273	A1-B1-C1-D1-E1-F1-G1-H1-I1-J1-K1-L1-M1-N1-O1-P1-Q3-R1

Table 14 — Percentage deviation of heuristic solutions from exact solutions for problem 2

Objectives (Minimize)	IGA-SCRP
Duration (Objective 1)	0.00
Cost (Objective 2)	0.7
Combined effect (Objective 3)	0.85

Table 15 — Solution corresponding to bi objective optimization in problem 2 using IGA-SCRP

Weights	w_t=1, w_c=0	w_t=0.8, w_c=0.2	w_t=0.7, w_c=0.3	w_t=0.6, w_c=0.4	w_t=0.5, w_c=0.5	w_t=0.4, w_c=0.6	w_t=0.3, w_c=0.7	w_t=0.2, w_c=0.8	w_t=0, w_c=1
Duration (Days)	69	70	70	72	72	73	74	74	89
Cost (Rs)	131623	130847	130847	127273	127273	126773	127880	126247	121414

Notations

Different terms are represented by the following notations:

m = Activity
m' = Successor activity
n = Unit
n' = Successor Unit
c = Crew option
K = Total number of activities
L = Total number of units
Q = Number of crew options available for each activity
d_{cm} = Durations per unit quantity of work of activity m
e_{cm} = Direct expenditure per unit quantity of work of activity m
qw_{mn}= Quantity of work of activity m in unit n.
ST_{mn} = Start time of activity m in unit n
FT_{mn} = Finish time of activity m in unit n
$T\ D$ = Total duration for the project
E = Total expenditure for the project
p_m= Penalty cost of activity m per day
LT_{mn} = Lateness time of activity m in unit n
IC =Indirect cost per day
DT_{mn} = Due time of activity m in unit n
E_o = Original expenditure
w_d = Specified weight assigned to the importance of duration
w_e = Specified weight assigned to the importance of expenditure

Conclusions

Scheduling of repetitive projects for a single crew model with the objectives of minimizing project duration and total expenditure, and bi-objective optimization of both of the above simultaneously is discussed in this paper. A modified genetic algorithm based heuristic methodology named IGA-SCRP is developed for scheduling large size problems. Results show that the heuristic methodology gives the solutions close to the optimum and average percentage deviation is negligible for all the objectives. It can be seen that both the methodologies are helpful for a decision maker in obtaining good schedules for a repetitive project scheduling problem.

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