Selection and Scheduling of Interdependent Projects using a Modified Genetic Algorithm

Manish Kumar, M L Mittal, Gunjan Soni and Dheeraj Joshi
Department of Mechanical Engineering
Malaviya National Institute of Technology
Jaipur, India
m81manishkumar@gmail.com, mlmittal.mech@mnit.ac.in, gsoni.mech@mnit.ac.in, dheerajjoshi25@gmail.com

Abstract
This paper deals with the problem of selection and scheduling of interdependent projects in an integrated manner. Two types of interdependencies among projects-mutual exclusiveness and complementariness are considered which are found to be of great practical importance. The problem seeks to maximize the total expected benefit from the selected projects wherein the benefit from a project is considered to be time-dependent. A mathematical model for the problem along with an illustrative example is presented. A modified genetic algorithm (GA) is developed to solve the real life problems. The proposed algorithm is evaluated on a set of randomly generated test problems with varying complexity. The performance of the proposed GA is compared with TS algorithm. The results show that proposed GA outperforms the TS algorithm in 10 test problems out of the total 15 problems generated in this study.

Keywords
Project selection and scheduling, Meta-heuristics, Genetic algorithm, Interdependencies

1. Introduction
Project firms pursue multiple projects sharing a pool of resources. The success of these projects largely depends on the selection of right mix of the projects hence and project selection is a crucial decision in a firm. Project selection problem involves the selection of most profitable projects from a large set of available candidate projects to optimize the firm's stated objective(s) respecting the resource, budget and other technical limitations. But models developed for project selection generally exclude project scheduling in the selection process (Coffin & Taylor, 1996a; 1996b). Traditionally, projects are selected first and then attempt is made to schedule these projects through various procedures in light of the available time and resources. If the selected projects cannot be scheduled, some of the projects may be dropped/changed, schedule may be relaxed or resource limit may be extended, ultimately resulting in a suboptimal portfolio. Thus project scheduling should be considered as an integral part of the project selection problem. This integrated problem of selection and scheduling of projects is known as project portfolio selection and scheduling problem (PPSSP). In recent years the PPSSP has gained attention of many researchers and has become an active field of research.
Maximizing the total expected benefit has been the popular objective in project selection problems as well as in integrated project selection and scheduling problems (PPSSP). Moreover, the benefit from a project is considered to be time-dependent (Chen & Askin, 2009). This is especially true in the case of projects related to introducing new products to the market. Early market entry helps the firm to acquire a larger market share than the late entrants This time-sensitive aspect of benefit in PPSSP is first considered by Chen & Askin (2009) and followed by Ghorbani & Rabbani (2009), Tofighian & Naderi (2015), Ganji et al. (2016), Amirian & Sahraeian (2017; 2018) and Kumar et al. (2018; 2019).
Further, there are inherent relationships between the projects. These interrelationships between the projects are known as interdependencies. There are three types of interdependencies defined in the literature namely: resource, benefit and technical (Aaker & Tyebjee, 1978; Fox et al., 1984) out of which technical interdependencies are most common which can be further divided into two types. One is mutual exclusiveness

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in which only one project from the subset can be included in the portfolio. Many authors have considered mutual exclusiveness in modelling the PPSSP (Ghazemzadeh et al., 1999; Ghorbani & Rabbani, 2009; Carazo et al., 2010; Huang & Zhao, 2014; Tofighian & Naderi, 2015; Wang & Song, 2016; Huang et al., 2016; Ganji et al., 2016; Amirian & Sahraeian, 2018; and Kumar et al., 2018; Kumar et al., 2019). Another technical interdependency is complementariness which can be described as the selection and rejection of complimentary projects from the subset together. Kumar et al. (2018) have considered the project complementariness in PPSSP. Despite the fact, the complementariness has been considered exclusively in project selection problems, but it is scantly addressed in PPSSP.

Resource constrained project scheduling problems (RCPSP) belongs to a very large family of NP-hard problems (Demeulemeester & Herroelen, 2006). The PPSSP becomes even more complex due to consideration of interdependencies. Because of such complex nature of the problem, the exact approaches are not suitable to solve the large sized problems. In such cases, meta-heuristics are employed to find a near optimal solution to the problem. Several meta-heuristics have been developed for the PPSSP in the literature (Ghorbani and Rabbani, 2009; Carazo et al., 2010; Huang and Zhao, 2014; Tofighian and Naderi, 2015; Ghahremani and Naderi, 2015; Amirian and Sahraeian, 2017; Kumar et al., 2018; Kumar et al., 2019). Evolutionary algorithms predominate in the research of applications of the meta-heuristics (Carazo et al., 2010). Genetic algorithm (GA) is an evolutionary algorithm and is widely applied to solve the complex engineering & optimization problems.

In this paper, we consider the PPSSP with two types of interdependencies and formulate a 0-1 integer model for the problem. The objective of the problem is to maximize the total expected benefit from the portfolio. The benefit from the projects is considered to be time-dependent. A modified genetic algorithm (GA) is proposed to solve the problem. Problem is tested on 15 randomly generated test problems, and results are compared with tabu search (TS) also developed for the problem.

The rest of the paper is structured as follows. Section 2 presents the mathematical formulation of the problem with an illustrative example. The methodology for the proposed GA is provided in Section 3. Computational experiences are described in Section 4. Finally, Section 5 concludes the paper.

2. Problem Statement

In this section, the problem under study is formulated and described in detail through an illustrative example. Let us consider a set of N candidate projects available for selection. The planning horizon is assumed to be fixed and is taken as T time periods. Some project may have due dates before which they must be completed if selected. K types of resources are required for the implementation of the selected projects and are available in limited quantity. Technical interdependencies: mutual exclusiveness and complementariness are considered in the model. The objective is to maximize the total expected benefit from a selected portfolio of projects. Further, the expected benefit from a project is assumed to be time dependent. Early scheduling of the projects is desirable whose return is highly sensitive to the completion time.

2.1 Mathematical Model

Decision variables and coefficients of the mathematical model are listed as below:

Technological coefficients and parameters:

P_{it} = expected profit if project i starts in period t.

d_i = duration of the project i.

r_{ik} = requirement of resource type k for project i in each time period.

R_{kt} = resource availability of type k in period t.

DD_i = Due date or milestone for the project i.

e = project mutually exclusive to project i, $\{e \epsilon E_i\}$

h = projects complementary to project i, $\{h \epsilon C_i\}$

Decision variable:

X_{it} = 1 if project i is selected and starts in period t

= 0 otherwise.

Formulation:

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Objective function:

Max $$Z = \sum_{i=1}^{N} \sum_{t=1}^{T-d_i+1} P_{it} * X_{it} \qquad (1)$$

Constraints:

$$\sum_{t=1}^{T-d_i+1} X_{it} \le 1 \qquad \forall\, i \qquad (2)$$

$$(t * X_{it} + d_i - 1) \le DD_i \qquad \forall\, i \qquad (3)$$

$$\sum_{i=1}^{N} \left(\sum_{j=\max\{1,t-d_i+1\}}^{\min\{t,T-d_i+1\}} X_{ij} \right) * r_{ik} \le R_{kt} \qquad \forall\, k, t \qquad (4)$$

$$\sum_{t=1}^{T-d_i+1} X_{it} = \sum_{t=1}^{T-d_h+1} X_{ht} \qquad \forall\, i, h \in C_i \qquad (5)$$

$$\sum_{t=1}^{T-d_i+1} X_{it} + \sum_{t=1}^{T-d_e+1} X_{et} \le 1 \qquad \forall\, i, e \in E_i \qquad (6)$$

$$X_{it} = \{0,1\} \qquad \forall\, i, t \le T - d_i + 1 \qquad (7)$$

Equation (1) defines the objective function for the problem which is to maximize the total expected benefit from the portfolio. The selection status and start time of each project are ensured by constraint (2). Constraint (3) ensures that each selected project is completed before its due date. The resource limitations are imposed by the constraint (4). Constraint (5) enforces the selection of complementary projects from a subset together. The mutual exclusiveness is imposed by constraint (6). Constraint (7) defines the decision variables.

2.2 Illustrative Example

In this section, a small problem and its feasible solution are presented to get a basic understanding of the model. Example problem has 4 candidate projects with the planning horizon of 9 time periods. Two resources are needed to carry out the projects and availability of each resource is fixed at 25 units per period. Table 1 provides the durations, due dates, resource requirements and interdependencies of the projects. Expected profits of projects in each time period is given in Table 2.

Table 1: Project durations, due dates, resource requirements and interdependencies

Projects	Duration	Due Date	Resource Requirements		Interdependencies	
			Type 1	Type 2	Mutually Exclusive	Complementary
1	4	7	14	11	3	
2	3	8	10	13		4
3	5	7	14	14	1	
4	5	9	15	12		2

Table 2: The expected profit in each time period

Projects	Time Periods								
	1	2	3	4	5	6	7	8	9
1	935	852	830	653	432	254	168	155	112
2	832	703	701	597	539	371	367	287	252
3	932	897	628	567	386	313	247	168	116

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4	954	850	679	674	620	306	233	199	144

Schedule of a feasible solution of the problem is shown in Table 3. Projects 1, 2 and 4 are selected and scheduled to start in periods 1, 1 and 5 respectively. Project 1 and 3 are mutually exclusive hence one of them (project 3) has not been selected. Projects 2 and 4 are selected together due to complementariness between them. The value of objective function equals 2387 units.

Table 3: A feasible solution and schedule

Projects	1	2	3	4	5	6	7	8	9
P1	1	1	1	1	0	0	0		
P2	1	1	1	0	0	0	0	0	
P3	0	0	0	0	0	0	0		
P4	1	0	0	0	1	1	1	1	1

Time Periods

3. Modified Genetic Algorithm

In this section, the procedure of the proposed genetic algorithm for PPSSP is described in detail. Genetic algorithm (GA) is an evolutionary algorithm inspired by natural evolution. This algorithm has been successfully applied to a variety of complex problems. In this study, maintaining the basic philosophy of the GA, the operators are modified and re-designed to suit the problem under study. Encoding scheme, population initialization and the operators of the proposed GA are explained as follows:

3.1 Encoding Scheme for proposed GA

The encoding scheme used in this paper is adapted from Ghorbani and Rabbani, (2009). A solution to the problem can be represented by a matrix of size $\{N \times T\}$. There are N rows equal to the number of candidate projects and T columns equal to the number of time periods. Each row represents a project, and each column represents a time period. The element a_{ij} represents the selection status and start time of project i in period j. The value '1' corresponds to the selected project. Table 4 shows a chromosome for proposed GA.

Table 4: Solution representation for proposed GA

Projects (p)	0	1	0	0	0	0	0		
	0	0	0	0	0	0	0	0	
	1	0	0	0	0	0			
	0	0	0	1	0	0	0	0	0

Time Periods (t)

3.2 Population Initialization

A population of the feasible chromosome with diversity is essential for the optimizing efficiency of the GA. The required chromosomes for the proposed GA are generated randomly to maintain the diversity. To obtain a feasible chromosome, projects are selected randomly one by one in light of the interdependencies and scheduled earliest possible satisfying the due date and resource limitations. All the chromosomes are obtained in the same manner.

3.3 Selection operator

A number of methods are available in the literature, but roulette wheel selection is the most efficient and widely applied method for selection. This method is used in the proposed GA to select the best chromosomes to be the part of the population for the next iteration.

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3.4 Crossover operator

The crossover operator starts with defining a crossover probability (p_c). Then, we generate M random numbers in the range [0-1]. If the random number (r) is less than the crossover probability, the corresponding chromosome is selected for crossover. If odd numbers of parents are selected then one more chromosome is selected randomly from the remaining chromosome to make the pairing easy. The pairing of the selected chromosomes to be parents is done randomly. Now, a row is selected randomly from the parent 1 in the pair and is copied to the parent 2 at the same place in the same pair maintaining the feasibility of the chromosome. This process gives the child 1 for pair undergone crossover. To obtain the child 2 for the same pair, the row is selected from the parent 2 and is placed in the parent 1 in the same way as done for child 1. Similarly, crossover is applied to all the pairs selected for crossover.

3.5 Mutation operator

The mutation operator starts with defining a mutation probability (p_m). Then, we generate random numbers equal to the number of children in the range [0-1]. If the random number (r) is less than the mutation probability (p_m) the corresponding chromosome is selected for mutation. Now, for mutation of a chromosome, a row is randomly selected and its start time is changed randomly maintaining the feasibility of the solution.

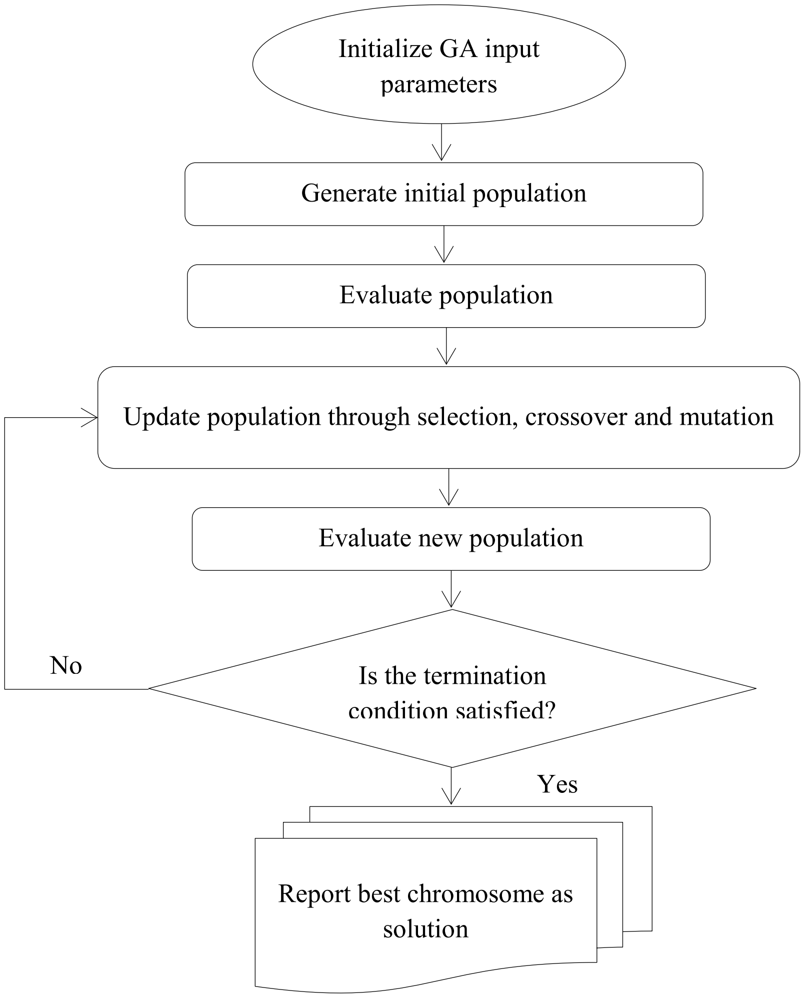

Figure 1: Basic genetic algorithm scheme

At the beginning, input parameters for GA are initialized. The proposed GA starts with initialization of input parameters (population size, crossover probability, mutation probability). The initial population of random

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feasible chromosomes is generated with the population initialization scheme. The objective function is taken as the fitness function for the problem and is calculated for each chromosome. The chromosomes are then updated using the selection, crossover and mutation operators designed for this problem. New chromosomes are evaluated and compared with the old chromosomes. Chromosomes which are superior to the previous one are considered to be the part of the current population for the next iteration. The algorithm is iterated for a predefined number of iterations. The best chromosome found so far is reported as the solution to the problem. The scheme for the basic genetic algorithm is given in Figure 1.

4. Computational Experience

This section evaluates the performance of proposed GA based on the comparison with Tabu Search (TS) developed for the problem. The scheme of TS algorithm proposed by Kumar et al. (2018; 2019) for PPSSP is used to develop TS for this study. Both the algorithms are coded in MATLAB 7.12 environment. The two algorithms are tested on 15 randomly generated instances.

4.1 Test problems

Test problems are generated randomly using the instance generation scheme proposed by Kumar et al. (2018). These test problems are of different size and complexity. The complexity of the problems is varied by reducing project durations, resource availability and enhancing the amount of interdependencies. A total of 15 test problems are generated.

4.2 Parameter settings

The population size (M) for the proposed GA is kept 20. The crossover probability (p_c) and mutation probability (p_m) are taken as 0.8 and .01 respectively. The size of the tabu list in TS algorithm is taken as 40 % of the problem size (number of projects). Termination criterion is set to 100 iterations for both the algorithms.

4.3 Comparison method

The performance of the proposed GA is compared with TS using percentage deviation method. The deviation of an algorithm's output is taken from the best value obtained by any of the two algorithms. The formula for the percentage deviation is given by equation (8).

$$PD = \frac{(B-X)}{B} * 100 \quad (8)$$

For a test problem, the value of objective function obtained by an algorithm is denoted by X. The best value found for the same instance by any of the two algorithms is denoted by B.

4.4 Results

Each test problem is solved 10 times by each algorithm. Average results are reported for comparison. The results for percentage deviation are presented in Table 5. From the results, it is clear that the proposed GA outperforms the TS algorithm. It is important to notice that for small-sized problems, there is little difference between the performances of the two algorithms. It can be seen that for problems LCP_01, LCP_02 and LCP_05 there is no difference in the performance of the two algorithms whereas the performance of proposed GA is slightly better than TS for LCP_03 and LCP_04. For the problems with medium complexity, the proposed GA performs better than TS for MCP_02, MCP_04 and MCP_05. As a major contribution of this work it can be seen that the proposed GA outperforms the TS for the problems with high complexity which are more prominent in real life scenario. To summarize, it is evident that the proposed GA is an effective solution technique for PPSSP.

Table 5: Outputs of the proposed GA and TS algorithm

Problem Type	Test Problem	Percentage Deviation	
		Proposed GA	TS

Low Complex	LCP_01	0	0
	LCP_02	0	0
	LCP_03	0	0.638215029
	LCP_04	0	0.454221481
	LCP_05	0	0
Medium Complex	MCP_01	0.041401633	0
	MCP_02	0	0.134870733
	MCP_03	3.223804823	0
	MCP_04	0	1.75189514
	MCP_05	0	2.84760098
High Complex	HCP_01	0	3.677492733
	HCP_02	0	3.07096362
	HCP_03	0	0.109865586
	HCP_04	0	0.898361811
	HCP_05	0	3.981051153

5. Conclusion

This paper considers the integrated problem of selection and scheduling of the interdependent projects. Two types of interdependencies among projects-mutual exclusiveness and complementariness are considered. The most beneficial projects are selected in the portfolio and are scheduled simultaneously. The total expected benefit is considered as the objective function to be optimized. The benefits from the projects are considered to be time-dependent. The problem is formulated in the form of a 0-1 integer program. A modified genetic algorithm (GA) is developed, and performance is compared with the Tabu Search (TS) algorithm existing in the PPSSP literature. Both the algorithms are evaluated on a set of 15 randomly generated test problems with varying complexity. The results show that proposed GA outperforms the TS algorithm in 10 test problems out of the total 15 problems generated in this study.

As a major contribution of this work, the developed algorithm promises a potential solution approach to tackle the large and real life project selection problems faced by various organizations. For future research, the problem can be extended to consider the multiple objective and dynamic selection and scheduling of projects.

References

Aaker, D. A., & Tyebjee, T. T., A model for the selection of interdependent R&D projects, *IEEE Transactions on engineering management*, vol. 2, pp. 30-36, 1978.

Amirian, H., & Sahraeian, R., Solving a grey project selection scheduling using a simulated shuffled frog leaping algorithm, *Computers & Industrial Engineering,* vol. 107, pp. 141-149, 2017.

Amirian, H., & Sahraeian, R., A hybrid integer grey programming for an integrated problem of project selection and scheduling with interval data, *Journal of Industrial and Production Engineering*, vol. 35, no. 4, 199-213, 2018.

Carazo, A. F., Gómez, T., Molina, J., Hernández-Díaz, A. G., Guerrero, F. M., & Caballero, R., Solving a comprehensive model for multiobjective project portfolio selection, *Computers & operations research*, vol. 37, no. 4, pp. 630-639, 2010.

Chen, J., & Askin, R. G., Project selection, scheduling and resource allocation with time dependent returns, *European Journal of Operational Research*, vol. 193, no. 1, pp. 23-34, 2009.

Coffin, M. A., & Taylor, B. W., Multiple criteria R&D project selection and scheduling using fuzzy logic, *Computers & Operations Research*, vol. 23, no. 3, pp. 207-220, 1996a.

Coffin, M. A., & TAYLOR III, B. W., R&D project selection and scheduling with a filtered beam search approach, *IIE transactions*, vol. 28, no. 2, pp. 167-176, 1996b.

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Demeulemeester, E. L., & Herroelen, W. S., *Project scheduling: a research handbook*, vol. 49, Springer Science & Business Media, 2006.

Fox, G. E., Baker, N. R., & Bryant, J. L., Economic models for R and D project selection in the presence of project interactions, *Management science*, vol. 30, no. 7, pp. 890-902, 1984.

Ganji, M., Alinaghian, M., & Sajadi, S. M., A new model for optimising simultaneously projects selection and resource-constrained project scheduling problem, *International Journal of Productivity and Quality Management*, vol. 19, no. 4, pp. 511-525, 2016.

Ghahremani, P., & Naderi, B., Solution algorithms for the project selection and scheduling problem with resource constraints and time dependent returns, *International Journal of Industrial and Systems Engineering*, vol. 19, no. 3, pp. 348-363, 2015.

Ghasemzadeh, F., Archer, N., & Iyogun, P., A zero-one model for project portfolio selection and scheduling, *Journal of the Operational Research Society*, vol. 50, no. 7, pp. 745-755, 1999.

Ghorbani, S., & Rabbani, M., A new multi-objective algorithm for a project selection problem, *Advances in Engineering Software*, vol. 40, no. 1, pp. 9-14, 2009.

Huang, X., & Zhao, T., Project selection and scheduling with uncertain net income and investment cost, *Applied Mathematics and Computation*, vol. 247, pp. 61-71, 2014.

Huang, X., Zhao, T., & Kudratova, S., Uncertain mean-variance and mean-semivariance models for optimal project selection and scheduling, *Knowledge-Based Systems*, vol. 93, pp. 1-11, 2016.

Kumar, M., Mittal, M. L., Soni, G., & Joshi, D., A hybrid TLBO-TS algorithm for integrated selection and scheduling of projects, *Computers & Industrial Engineering*, vol. 119, pp. 121-130, 2018.

Kumar, M., Mittal, M. L., Soni, G., & Joshi, D., A Tabu Search Algorithm for Simultaneous Selection and Scheduling of Projects, In *Harmony Search and Nature Inspired Optimization Algorithms*, Springer, Singapore, pp. 1111-1121, 2019.

Tofighian, A. A., & Naderi, B., Modeling and solving the project selection and scheduling, *Computers & Industrial Engineering*, vol. 83, pp. 30-38, 2015.

Wang, B., & Song, Y., Reinvestment strategy-based project portfolio selection and scheduling with time-dependent budget limit considering time value of capital, *Proceedings of the 2015 International Conference on Electrical and Information Technologies for Rail Transportation*, Springer, Berlin, Heidelberg, pp. 373-381, 2016.

Biographies

Manish Kumar is a Research Scholar in the Department of Mechanical Engineering at the Malaviya National Institute of Technology Jaipur, India. He received his Master's degree in Manufacturing and System Engineering from Malaviya National Institute of Technology Jaipur, India in 2013. His research interests include project selection & scheduling, facility planning and artificial intelligence applications.

M. L. Mittal is professor in Department of Mechanical Engineering at Malaviya National Institute of Technology Jaipur, India. He obtained Bachelor of Engineering Degree in Mechanical Engineering from University of Rajasthan (India) in 1988, and Master of Engineering in Production Engineering form M.S. University of Baroda (India) in 1991. He obtained PhD Degree in Industrial Engineering from Indian Institute of Technology, Delhi (India) in 2006. He has teaching experience of about 25 years to both UG and PG (MTech and MBA) and PhD level. His research interests include production and operations management, project management & scheduling, and artificial intelligence. He has published more than 70 papers in international and national journals and conference proceedings.

Gunjan Soni is assistant professor in Department of Mechanical Engineering at Malaviya National Institute of Technology Jaipur, India. He received his Bachelor of Engineering Degree in Mechanical Engineering from the University of Rajasthan (India), and Master's degree in Industrial Engineering from Indian Institute of Technology, Delhi (India). He obtained PhD Degree from the Birla Institute of Technology and Science, Pilani (India). He has an experience of over 12 years in teaching and research. His research areas include supply chain management, risk analysis, production planning, and artificial intelligence.

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Dheeraj Joshi is a Research Scholar in the Department of Mechanical Engineering at the Malaviya National Institute of Technology Jaipur, India. He is also Associate Professor at the Department of Mechanical Engineering at SKIT, Jaipur, India. He received his Bachelor's and Master's degree in Production and Industrial Engineering from MBM Engineering College, Jodhpur, India in 2002 and 2011 respectively. His research interests include project management and scheduling, and applications of artificial intelligence techniques.

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