Comparing optimization modeling approaches for the multi-mode resource-constrained multi-project scheduling problem

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Abstract

Purpose – Construction firms keep minimal resources to maintain productive working capital. Hence, resources are constrained and have to be shared among multiple projects in an organization. Optimal allocation of resources is a key challenge in such situations. Several approaches and heuristics have been proposed for this task. The purpose of this paper is to compare two approaches for multi-mode resource-constrained project scheduling in a multi-project environment. These are the single-project approach (portfolio optimization) and the multi-project approach (each project is optimized individually, and then heuristic rules are used to satisfy the portfolio constraint).

Design/methodology/approach – A direct search algorithm called Probabilistic Global Search Lausanne is used for schedule optimization. Multiple solutions are generated that achieve different trade-offs among the three criteria, namely, time, cost and quality. Good compromise solutions among these are identified using a multi-criteria decision making method, Relaxed Restricted Pareto Version 4. The solutions obtained using the single-project and multi-project approaches are compared in order to evaluate their advantages and disadvantages. Data from two sources are used for the evaluation: modified multi-mode resource-constrained project scheduling problem data sets from the project scheduling problem library (PSPLIB) and three real case study projects in India.

Findings – Computational results prove the superiority of the single-project approach over heuristic priority rules (multi-project approach). The single-project approach identifies better solutions compared to the multi-project approach. However, the multi-project approach involves fewer optimization variables and is faster in execution.

Research limitations/implications – It is feasible to adopt the single-project approach in practice; realistic resource constraints can be incorporated in a multi-objective optimization formulation; and good compromise solutions that achieve acceptable trade-offs among the conflicting objectives can be identified.

Originality/value – An integer programming model was developed in this research to optimize the multiple objectives in a multi-project environment considering explicit resource constraints and maximum daily costs constraints. This model was used to compare the performance of the two multi-project

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environment approaches. Unlike existing work in this area, the model used to predict the quality of activity execution modes is based on data collected from real construction projects.

Keywords Optimization, Scheduling, Project management, Decision support systems, Construction planning

Paper type Research paper

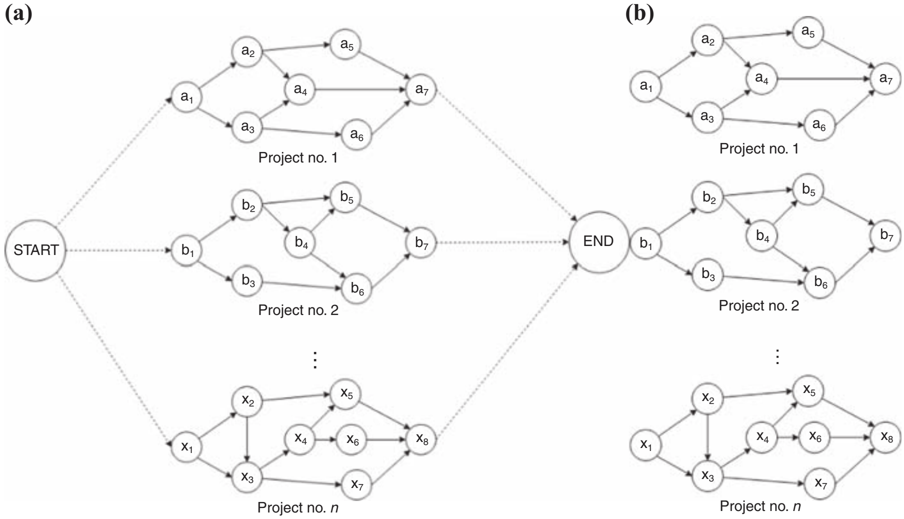
1. Introduction

Traditional techniques such as the Critical Path Method and the Program Evaluation and Review Technique consider only unconstrained resource state (Goncalves *et al.*, 2008). However, construction companies work in a constrained resource environment. Constraints on resources are explicitly modeled in the mathematical formulation of resource-constrained project scheduling problems (RCPSP) (Koulinas and Anagnostopoulos, 2012). RCPSP is defined as scheduling of activities under precedence and resources constraints to minimize the project duration (Hartmann and Briskorn, 2010). Based on the project environment and activity execution modes, RCPSP could be classified as classical RCPSP, multi-mode RCPSP (MRCPSP), resource-constrained multi-project scheduling problem and multi-mode resource-constrained multi-project scheduling problem (MRCMPSP). MRCMPSP has the highest complexity compared to the other variations and reflects higher practical relevance. More than 90 percent of all international projects are executed in a multi-project environment (Payne, 1995). Herroelen (2005) mentions that even a small improvement in multi-project management would yield a significant benefit.

The presence of multiple objectives, such as time, cost and quality adds further complexity. The trade-offs amongst conflicting objectives have been considered to identify ways to complete projects within time and budget under limited resources (Tran and Long, 2018). The schedule performance of the project depends on the relationship between the allocated amount of resources and the duration of activities. Many activity execution modes are possible with different combinations of construction methods, materials and crew sizes (El-Rayes and Kandil, 2005; Elbeltagi *et al.*, 2016). In "multi-mode" RCPSP, the goal is to identify the best combination of activity execution modes such that the project duration is minimized. Most previous researchers approached the time-cost tradeoff problem in a single-project environment (Aminbakhsh and Sonmez, 2016; Feng *et al.*, 1997). In practice, decision making in a multi-project environment is complex. Contractors must deliver quality work to survive in a competitive environment (Kong *et al.*, 1997). Due to the conflicting nature of time, cost and quality objectives, acceptable schedules can be obtained only by evaluating relative sacrifices and gains through optimally allocating different types and amounts of resources. Project quality is a criterion that has been largely ignored in previous studies on schedule optimization in a multi-project environment. The quality of activities can be estimated through quality performance indicators (El-Rayes and Kandil, 2005). Developed countries use standard checklists to measure the activity quality in terms of workmanship (BCA Singapore, 2017; HKHA Hong Kong, 2016; Kam *et al.*, 2015). However, quantitative data related to quality collected from real projects have not been used for resource optimization.

Two network modeling approaches have been proposed to handle the multi-project environment (Kurtulus and Davis, 1982): single-project approach and multi-project approach (Figure 1). In the multi-project approach, each project is optimized individually, whereas in the single-project approach all the projects are considered as part of a single network using fictitious start and end activities. In the multi-project approach, each individual optimization does not consider the overall resource availability at the organization level. Hence, after completing one round of optimization, projects might have to be rescheduled if resource constraints are found to be violated at the portfolio level. Priority rules have been proposed to help in this process. These are described in the next section.

The primary aim of this research is to compare the multi-project environment approaches, single-project approach and multi-project approach for multiple objectives under the



Notes: (a) Single-project approach; (b) multi-project approach

Figure 1. Network modeling approaches in a multi-project environment (MPE)

resource-constrained project scheduling situation. More specifically, it is examined whether the heuristic rules proposed for the multi-project approach are able to generate solutions with comparable project performance. The paper is organized as follows: Section 2 reviews the studies related to time, cost and quality optimization, and resource-constrained project scheduling. The proposed approach in this research is presented in Section 3. A mathematical model is formulated for optimizing MRCMPSP is given in Section 4. The model evaluation and validation are described in Sections 5 and 6, respectively. Section 7 discusses the results of modified benchmarking data sets and sample case study projects. Finally, Section 8 contains the results and possible future research directions.

2. Studies on resource-constrained project scheduling problems in a multi-project environment

Managing a multi-project environment is arduous and challenging (Blismas *et al.*, 2004; Patanakul and Milosevic, 2009). Resource optimization is essential to improve portfolio performances (Kannimuthu *et al.*, 2018; Ugwu and Tah, 2002). However, there is not much literature on the MRCMPS category involving multi-objective optimization. Existing research on RCPSPs in the multi-project environment is summarized in this Section by classifying them according to the mathematical modeling approach, the optimization objectives, and the solution strategies. Mathematical models include integer programming (IP), mixed integer programming (MIP), linear programming and constraint programming. Most studies related to multi-project environment consider only one objective, that is, duration, and other objectives are ignored. In general, two types of solution strategies have been used, exact and approximate. Remaining sub-sections are structured based on these broad categories.

2.1 Mathematical modeling approach

2.1.1 Integer programming (IP). Previous researchers have developed various IP mathematical models for RCPSPs addressing different aspects, such as, peak of total resource requirements and average tightness of the constraints on resources (Browning and Yassine, 2010; Kurtulus and Davis, 1982), decomposition of multiple projects (Deckro *et al.*, 1991), analysis of scheduling schemes (Lova and Tormos, 2001), decentralized multi-project scheduling with resource transfers (Adhau *et al.*, 2013), multiple mode of activities (Monghasemi *et al.*, 2015), optimal trade-offs between different projects' objectives (El-Abbasy *et al.*, 2017), etc. Some authors have reduced the MRCMPS problem to MRCPSP by determining the resources to be dedicated to individual projects (Beşikci *et al.*, 2015). Many previous researchers have optimized multiple objectives in a single-project environment (Kannimuthu *et al.*, 2019; Luong *et al.*, 2018; Tran and Long, 2018).

2.1.2 Mixed integer programming (MIP). MIP mathematical models have been developed for RCPSPs, for example, Chiu and Tsai (2002), Rostami *et al.* (2017) and Tavana *et al.* (2014). Khalili-Damghani *et al.* (2015) solved multi-objective trade-off problems under generalized precedence relations using MIP. Geiger (2017) proposed a mathematical model for optimizing the two objectives, total makespan (TMS) and total project delay (TPD). Mittal and Kanda (2009b) present an IP model for inter-project resource transfers.

2.1.3 Linear programming (LP). Many researchers have used LP for addressing RCPSPs. A model for two-stage prioritization of multiple projects for resource allocation is described (Mittal and Kanda, 2009b). The financial cost is optimized by Alavipour and Arditi (2018), and profit is maximized (Alavipour and Arditi, 2019a). Time-cost trade-off analysis to minimize total cost and maximize profit is described (Alavipour and Arditi, 2019b).

2.1.4 Other mathematical models. Liu and Wang (2010) developed a constraint programming model incorporating cash flow and financial requirements. Liu and Lu (2019) extended constraint programming model to allocate finite resources to multiple projects and reduce the interproject resource transfer.

2.2 Optimization objectives

Previous research is categorized based on the number of optimization objectives as follows:

(1) Research works related to single-objective variants:

- minimizing TPD (Browning and Yassine, 2010; Deckro *et al.*, 1991; Geiger, 2017; Kurtulus and Davis, 1982; Lova and Tormos, 2001; Sonmez and Uysal, 2014; Wauters *et al.*, 2014).
- maximizing net present value (Alavipour and Arditi, 2018, 2019a, b; Chiu and Tsai, 2002; Liu and Wang, 2010).
- minimizing total costs (Beşikci *et al.*, 2015; Liu and Lu, 2019; Mittal and Kanda, 2009a, b; Rostami *et al.*, 2017).
- minimizing average project delay (Adhau *et al.*, 2012, 2013; Wang *et al.*, 2017).

(2) Research works related to multi-objective variants:

- optimizing time, cost and quality (Kannimuthu *et al.*, 2019; Khalili-Damghani *et al.*, 2015; Luong *et al.*, 2018; Monghasemi *et al.*, 2015; Mungle *et al.*, 2013; Tavana *et al.*, 2014).
- optimizing time, cost, resource moments and cash flow (El-Abbasy *et al.*, 2017; Elbeltagi *et al.*, 2016; Farshchian and Heravi, 2018).
- optimizing project duration, cost and risk (Tran and Long, 2018).

2.3 Solution strategies

Most works on resource optimization use approximate methods which can be divided into priority rule-based heuristics, classical meta-heuristics and non-standard meta-heuristics (Kolisch and Hartmann, 2006). Important priority rule-based heuristics include minimum slack (MINSLK), minimum late finish time (MINLFT) and maximum total work content

(MAXTWK). Depending on the rule used, the project with MINSLK, MINLFT or MAXTWK is given priority during scheduling. These rules have been evaluated by various authors as described in Section 2.3.2.1.

2.3.1 Exact methods. Deckro *et al.* (1991) used a decomposition approach to solve the multi-project, resource-constrained scheduling problem to minimize the total activity throughput time. Liu and Wang (2010) established a profit optimization model for multi-project scheduling problems using constraint solving. Menesi and Hegazy (2014) developed a constraint programming model to optimize the project duration using IBM-ILOG-CPLEX-CP solver engine. Geiger (2017) used a variable neighborhood search, together with the iterated local search to minimize TMS and TPD. Alavipour and Arditi (2018) optimized financing inflow and outflow costs using LP solver. Liu and Lu (2019) allocated finite resources to multiple projects and reducing the interproject resource transfer using CP optimizer engine.

2.3.2 Approximate methods. 2.3.2.1 Heuristic methods. Kurtulus and Davis (1982) classified the capability of multi-project scheduling rules to minimize TPD according to the average resource loading factor and average utilization factor. They concluded that MINSLK satisfies both the location of the peak and tightness of the resources. Chiu and Tsai (2002) incorporated both the project delay penalty and early completion bonus to maximize the average total project net present value. Lova and Tormos (2001) analyzed the effect of priority rules and found that MINLFT with multi-project approach performed the best. Mittal and Kanda (2009b) proposed a two-stage prioritization process for resource allocation. When the objective is to minimize the makespan, they suggest allocating resources first to the projects with the maximum remaining critical path length. If the objective is to minimize mean project delay, the suggestion is to allocate resources first to the projects with minimum remaining work. They found that MINLFT produces the best schedules almost comparable to that produced by MINSLK and minimum late start time (MINLST). Browning and Yassine (2010) confirmed the superiority of the maximum total work content-late start time (TWK-LST) over MINSLK, and MAXTWK from an individual project manager's perspective (Lova and Tormos 2001). Wang *et al.* (2017) recommended the best priority rules, from a project and portfolio managers perspective. Priority heuristic rules have been extensively used in practice. However, heuristic models are problem dependent, which implies that the rules specific to a model cannot be equally applied for all problems (Leu *et al.*, 2000), and do not guarantee an optimal solution.

2.3.2.2 Meta-heuristic methods. Adhau *et al.* (2012) developed a novel distributed multi-agent system using auctions-based negotiation (DMAS/ABN) for resolving resource conflicts and allocating multiple different types of shared resources amongst competing projects to minimize the average project delay. Adhau *et al.* (2013) extended this approach to consider resource transfer times in a multi-project environment. Wauters *et al.* (2014) minimized the TPD and the TMS using nine different search strategies. Genetic algorithm and its variants, such as fuzzy clustering GA, non-dominated sorting GA (NSGA-II), backward-forward hybrid GA, multi-objective GA have been used to optimize single and multiple objectives (Beşikci *et al.*, 2015; El-Abbasy *et al.*, 2017; Monghasemi *et al.*, 2015; Mungle *et al.*, 2013; Sonmez and Uysal, 2015; Tavana *et al.*, 2014). Khalili-Damghani *et al.* (2015) proposed dynamic self-adaptive multi-objective particle swarm optimization (DSAMPSO) to minimize the overall project duration and cost and maximize the project quality. Elbeltagi *et al.* (2016) modified particle swarm optimization with a new evolution strategy to optimize the schedule considering time, cost, resource moments and cash flow in a single-project environment. Luong *et al.* (2018) extended previous work by adding quality as an objective and used opposition-based multiple objective differential evolution (DE) for optimizing multiple objectives. Rostami *et al.* (2017) proposed a decentralized resource-constrained multi-project scheduling problem considering periodic services to minimize the cost and the construction cost of the resource pool using a combinatorial artificial bee colony algorithm. Probabilistic assessment of uncertainties and risks related to time, cost and revenue of portfolio of projects have been resolved using stochastic agent simulation model without considering contractual parameters and quality aspects (Farshchian and Heravi, 2018). Tran and Long (2018) proposed adaptive multiple objective DE for minimizing time, cost and risk in a resource-unconstrained single-project environment. Alavipour and Arditi (2019a, b) considered financing alternatives for a single-project environment using GA.

2.4 Point of departure

None of the existing works critically compared the two multi-project environment approaches, namely, single-project approach and multi-project approach for optimizing multiple objectives of time, cost and quality. The limitations of recent works in the relevant focus areas are mentioned in Table I. Multi-objective optimization in a multi-project environment under uncertainties of activity execution modes has not been attempted yet. The mathematical models in earlier studies have not explicitly included costs due to violation of quality constraints (Alavipour and Arditi, 2019a; Luong *et al.*, 2018; Monghasemi *et al.*, 2015; Mungle *et al.*, 2013). Existing benchmark problem data sets such as project scheduling problem library (PSPLIB) do not contain data related to cost and quality. Table I summarizes the modeling approach, the objective, the solution approach and the limitations of earlier studies. Time-cost-quality trade-off is a combinatorial optimization and belongs to the class of NP-hard problem (Mungle *et al.*, 2013). Multi-project environment adds further complexity. Meta-heuristic methods provide an optimal/near-optimal solution, which is highly beneficial for construction planners and decision makers. Therefore, developing or adopting new solution approaches for the multi-project environment is highly recommended (Alavipour and Arditi, 2018; Menesi and Hegazy, 2014).

3. The methodology for comparing the single-project approach and the multi-project approach in a multi-project environment

In this work, two different multi-project environment approaches (Figure 1) are compared in terms of the performance parameters of the solutions obtained by these approaches. The evaluation and validation are performed using two sources of data: modified benchmarking data sets selected from PSPLIB (see Section 5) and sample case studies of real projects in India (Section 6). For each project instance, five solutions are obtained by optimizing time, cost and quality individually as well as through two different methods for identifying the best compromise. Further, the portfolio constraint on maximum daily cost is compared under two scenarios. Inferences are made about the efficiency of the two approaches by comparing the time, cost and quality of these solutions obtained.

The overall methodology is illustrated in Figure 2. An integer programming model is developed to optimize time, cost and quality in a multi-project environment (for details, see Section 4). Solution of the optimization problem involves generation of non-dominated solutions using a suitable optimization algorithm and identification of a compromise solution by specifying acceptable trade-offs among conflicting objectives. A global search algorithm called Probabilistic Global Search Lausanne (PGSL) is used for generating the Pareto front. PGSL is a direct search algorithm in which the search space is sampled using a probability density function (PDF) (Raphael and Smith, 2003). The PDF is updated dynamically as the search progresses such that the probability of generating better solutions is improved without getting trapped in local minima (Raphael and Smith, 2005). Even though, the original PGSL algorithm handles only a single objective, it can be used to generate the Pareto front by taking different combinations of weights of objectives and repeating the optimization many times. All the solutions generated during the process are filtered according to the criterion of Pareto optimality. After generating the Pareto front, an

Table I. Review of earlier studies on time, cost and quality optimization, and resource-constrained project scheduling

Author (year)	Modeling approach	Objective	Solution approach	Systematic comparison of SPA and MPA with multiple objectives	Limitations
Kurtulus and Davis (1982)	Integer programming	Minimize TPD by classifying the performance of multi-project scheduling rules according to the peak of total resource requirements and the rate of resource utilization	Heuristic priority rules	X	Single objective optimization
Deckro *et al.* (1991)	Integer programming	Minimize total activity throughput time	Decomposition approach	X	Single objective optimization
Lova and Tormos (2001)	Integer programming	Minimize multi-project duration increase or mean project delay	Heuristic priority rules	X	Single objective optimization
Chiu and Tsai (2002)	Mixed-integer nonlinear programming	Maximize average total project net present value considering delay penalty and early completion bonus	Heuristic priority rules	X	Single objective optimization
Mittal and Kanda (2009a)	Integer linear programming	Minimize total costs due to penalty/reward for tardy/early projects and idleness and transfer of resources	LINGO solver	X	Single objective optimization
Mittal and Kanda (2009b)	Linear programming	Propose two-stage prioritization process of activities for resource allocation	Heuristic priority rules	X	Single objective optimization
Liu and Wang (2010)	Constraint programming	Maximize the (profit) difference between overall payment and expenditure	Constraint optimization	X	Single objective optimization
Browning and Yassine (2010)	Integer programming	Analyze 20 priority rules for static RCMPSP with project lateness and portfolio lateness	Heuristic priority rules	X	Single objective optimization
Adhau *et al.* (2012); Adhau *et al.* (2013)	Integer programming	Minimize APD	Distributed MAS using auctions-based negotiation	X	Single objective optimization
Mungle *et al.* (2013)	Integer linear programming	Minimize project time, total cost while maximizing the project quality through selecting the optimal/near-optimal combination of subcontractors	Fuzzy clustering Genetic algorithm (FCGA)	X	Single-project environment
Tavana *et al.* (2014)	Mixed-integer nonlinear programming	Minimize overall time and cost and maximize the overall quality of the project	Epsilon constraint procedure; NSGA-II	X	Single-project environment

(*continued*)

Table I.

Author (year)	Modeling approach	Objective	Solution approach	Systematic comparison of SPA and MPA with multiple objectives	Limitations
Wauters *et al.* (2014)	Integer linear programming	Minimize TPD and TMS	Nine different search strategies evaluated	X	Single objective optimization
Sonmez and Uysal (2015)	No details	Minimize the maximum of project completion times	Backward-forward hybrid genetic algorithm (BFHGA)	X	Single objective optimization
Khalili-Damghani *et al.* (2015)	Mixed-integer programming	Minimize overall time and cost and maximize the quality of the project	Classic and efficient epsilon-constraint method, DSAMOPSO	X	Single-project environment; random activity execution modes
Monghasemi *et al.* (2015)	Integer programming	Identify best Pareto solution for multiple objectives, time, cost and quality	Multi-objective GA, evidential reasoning	X	Single-project environment
Beşikci *et al.* (2015)	Integer programming	Minimize total weighted tardiness costs of projects	Two-phase and a monolithic GA	X	Single objective optimization
Elbeltagi *et al.* (2016)	Integer programming	Optimize schedule considering time, cost, resource moments and cash flow	Particle swarm optimization (PSO) with new evolution strategy	X	Single-project environment
El-Abbasy *et al.* (2017)	Integer programming	Optimize trade-offs among schedule, cash-flow, and resource-based objectives	Non-dominated sorting genetic algorithm II	X	Quality is not one of the proposed objectives
Wang *et al.* (2017)	No details	Measures average relative delay of individual sub-projects and the aggregated multi-project under a stochastic environment	Full factorial experiment	X	Single objective optimization; artificial cases
Rostami *et al.* (2017)	Mixed-integer linear programming	Minimize the cost associated with the project's completion times (operational) and the cost of the resource pool (strategic level)	Combinatorial artificial bee colony (CABC) algorithm	X	Single objective optimization
Geiger (2017)	Mixed-integer linear programming	Minimize TMS and TPD	Variable neighborhood search (local search)	X	Single objective optimization
Tran and Long (2018)	Integer programming	Minimize project duration, cost and risk	Adaptive multiple objective differential evolution (DE)	X	Single-project environment; resource constraints are not considered

(*continued*)

Author (year)	Modeling approach	Objective	Solution approach	Systematic comparison of SPA and MPA with multiple objectives	Limitations
Farshchian and Heravi (2018)	No details	Probabilistic assessment of uncertainties and risks related to time, cost, and revenue of portfolio of projects	Stochastic agent simulation model	X	Contractual parameters and quality not considered
Luong *et al.* (2018)	Integer programming	Minimize the overall time and cost and maximize the project quality	Opposition-based multiple objective differential evolution	X	Single-project environment
Alavipour and Arditi (2018)	Linear programming	Optimize financing inflow and outflow costs	LP solver	X	Single-project environment; trade-off not considered
Kannimuthu *et al.* (2019)	Integer programming	Optimize time, cost and quality under maximum daily costs (resource) constraints	Probabilistic Global Search Lausanne	X	Single-project environment
Liu and Lu (2019)	Constraint programming	Allocate finite resources to multiple projects and reduce the interproject resource transfer	CP optimizer engine (IBM ILOG CPLEX)	X	Single objective optimization; project deadlines, penalty not addressed
Alavipour and Arditi (2019a); Alavipour and Arditi (2019b)	Linear programming	Maximize profit and minimize financing costs under cash flow and financing alternatives	Genetic algorithm	X	Single objective optimization; single-project environment

Notes: X, absence; SPA, single-project approach; MPA, multi-project approach; TPD, total project delay; TMS, total makespan; APD, average project delay

Table I.

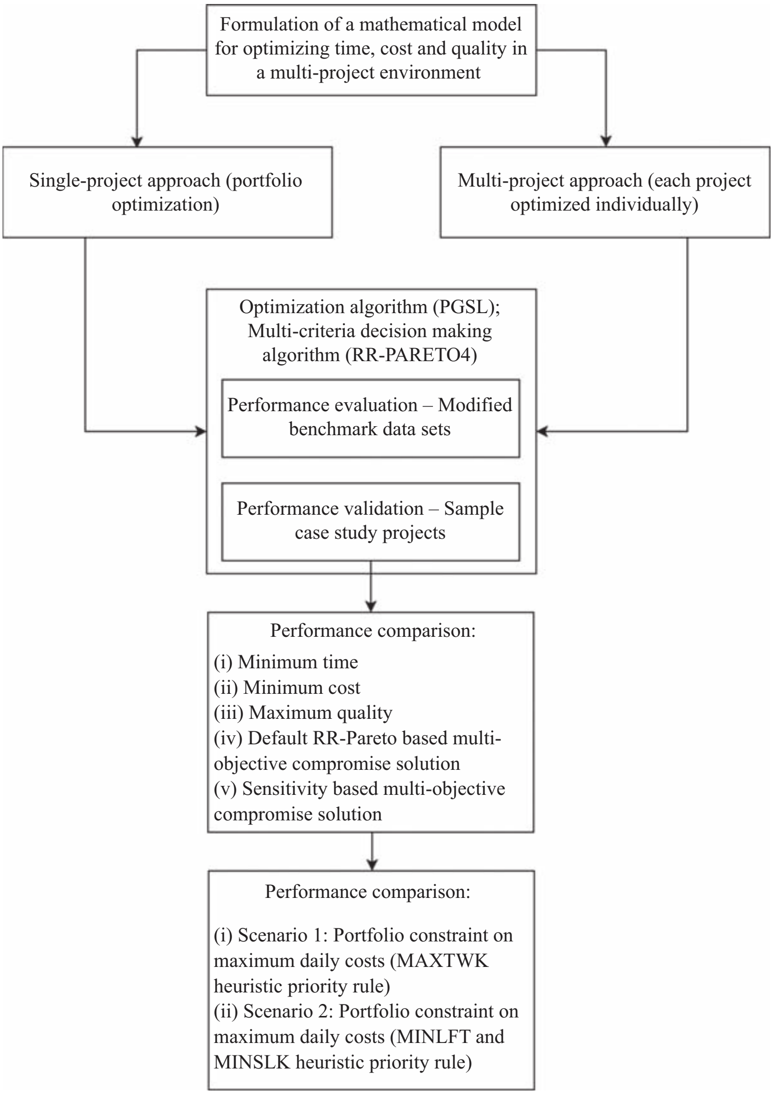


Figure 2.
Methodology for comparing the multi-project environment approaches

algorithm called Relaxed Restricted Pareto Version 4 (RR-PARETO4) (Raphael, 2011) is used to select a single solution from the set of non-dominated solution. In the RR-PARETO4 algorithm, the best compromise solution is chosen based on the order of the objectives (according to their importance) and the sensitivity of each objective (Kannimuthu *et al.*, 2019). The sensitivity parameter specifies how much sacrifice in the value of each objective is acceptable to the user. The algorithm works by iteratively removing solutions lying outside the sensitivity band of each objective, if the user does not specify the sensitivity parameter, or if multiple solutions remain after applying sensitivity-based filtering, a default selection algorithm is used. In the default selection, the best compromise solution is the one in which the net sacrifice in the value of the most important objective is equal to the average gain in the values of other objectives, when all the Pareto optimal solutions are compared.

3.1 Single-project approach

In this approach, multiple projects are considered together by introducing start and end dummy activities (Figure 1). Salient features of this approach are the following:

(1) All the project activities are scheduled under precedence and resource constraints. Constraints are set on maximum duration, maximum cost and minimum quality for each project.

(2) Resource constraints and maximum daily costs are set at the portfolio level.

(3) Optimization objectives are the portfolio performance parameters, which are, duration, cost and quality. Two settings are tested to identify the compromise solution by specifying the sensitivity parameter and by using the default RR-Pareto filtering method.

3.2 Multi-project approach

In this approach, each project is optimized individually without considering other projects (Figure 1). Resource utilization at the portfolio level is not considered during each individual optimization. Salient features of this approach are given below:

(1) All the project activities are scheduled under precedence and resource constraints.

(2) Resource constraints and maximum daily costs are set at the project level.

(3) Optimization objectives are the project performance parameters, which are duration, cost and quality. Two settings are tested to identify the compromise solution as in the single-project approach.

(4) After optimization of individual projects, constraints at the portfolio level are checked and selected projects are rescheduled according to heuristic rules. If the portfolio constraint is to limit the maximum daily costs, two heuristic priority rules are used, MAXTWK; or MINSLK and MINLFT.

3.3 Portfolio constraint on maximum daily costs

Even though the optimization model is able to accommodate constraints on different types of resources, such as equipment, in the present study, resource usage is modeled implicitly through the use of daily costs of resources. This is justified because, in many construction companies, equipment are rented, and resource availability depends on cash flow. Individual project managers prepare the schedule for their projects, considering the constraint of maximum daily costs at the project level. Then, the portfolio manager will check whether the sum of maximum daily costs of all the projects are still under the acceptable level, if yes, all the projects will be carried out with the initial plan, otherwise, the portfolio manager will use the heuristic priority rule to select the project to reschedule the activities in order to bring down the maximum daily costs. The single-project approach can meet the portfolio constraints without using heuristic priority rules because it explicitly checks the constraint on the maximum daily costs at the portfolio level, whereas the multi-project approach has to use heuristic priority rules, such as MAXTWK, or MINSLK and MINLFT.

4. Formulation of a mathematical model

Consider a project p with n activities and each activity i can have multiple execution modes. Time, cost and quality are the project performance parameters that are optimized based on the concept of Pareto optimality. The mathematical formulation in this research is an extended version of previous work by Kannimuthu *et al.* (2019) in a single-project environment. The total cost of the project includes two components: direct and indirect costs; costs due to constraint violations, i.e. penalties for exceeding the project due date, and not meeting the quality set by the user; as well as a bonus for the early completion and quality satisfaction. The quality of the project is calculated based on the construction quality assessment system (CONQUAS), using a database of past projects in which the CONQUAS scores of each activity executed in a particular mode is stored.

The model assumptions are:

- each activity can be executed in one of the many possible modes;
- activity cannot start until all preceding activities have been completed;
- activity pre-emption is not permitted;
- identified activity execution modes apply to similar kinds of projects; and
- uniform maximum daily costs throughout the project duration.

The indices and input parameters:

- n: set of project activities, $I,j \in n$, where j is a successor activity of i.
- M: set of activity execution modes, $m \in M$.
- Lp: project network path p.
- L: set of project network paths, $Lp \in L$.
- I: activity i in path Lp.
- C_p^{UB}: upper bound of cost in project p.
- Q_p^{LB}: lower bound of quality of project p.
- Q_{UB}: upper-bound of the project quality (100 percent).
- D_p: contractual due date of the project p.
- t_p^{im}: duration of activity i in project p with mode m.
- C_{p1}: direct and indirect costs of project p.
- C_{p2}: costs of constraint violation in project p.
- dc_p^{im}: direct cost of activity i in project p with mode m.
- ic_p: indirect cost of the project p per period.
- β_{pt}, β_{pq}: penalty of time and quality violation for project p, respectively.
- I_{pt}, I_{pq}: bonus for early completion and quality satisfaction for project p, respectively.
- w_{pt}, w_{pc}, w_{pq}: weight of time, cost and quality objective of project p, respectively.
- Q_{ie}^m: quality performance of activity i of element e in mode m.
- Q_i^m: quality of activity i in mode $m = \sum_{e \in E} Q_{ie}^m$.
- $Q_{p,\ min}$: minimum quality of project p among the selected activity modes.
- $Q_{p,\ avg}$: average quality of project p among the selected activity modes.
- α_p: relative importance between the minimum and average quality of project p.
- x: auxiliary variable that represents a time step in the range [0, T].

- $A_{imx(p)}$: 1 if activity i of project p is performed at time step x; that is, if $S_{i(p)} \leqslant x < (S_{i(p)} + t_p^{im})$, 0 otherwise.

  RUx(p): resource utilization (direct costs) at time step x of project p: $\left(\sum_i \left(\frac{dc_p^{im}}{t_p^{im}}\right) X_p^{im} A_{imx(p)}\right)$.
- RU_{UB}: upper-bound of the maximum daily resource utilization (direct costs).
- $RR_{k(p)}$: renewable resource type k of project p.
- $RR_{UB(k)(p)}$: upper-bound of the renewable resource type k of project p.

Decision variable:

- X_p^{im}: 1 if activity i of project p executed in mode m, 0 otherwise.
- $S_{i(p)}$: start time of activity i of project p.

Mathematical model:

$$\text{Min multiproject duration}\left(T_p\right) = \max_{L_p \in L} \max_{i \in n} \left(\sum_{m \in M} \left(S_{i(p)} + t_p^{im}\right) X_p^{im} \right), \tag{1}$$

$$\begin{aligned} \text{Min multiproject cost}\left(C_p\right) = \sum_{p \in P} \left(C_{p1} + C_{p2}\right) = \sum_{p \in P} \Bigg(\Bigg[\Bigg(\sum_{i \in n} \sum_{m \in M} dc_p^{im} X_p^{im} \Bigg) \\ + \left(ic_p \times T_p\right) + \left[\beta_{pt} \left[T_p - D_p\right]^+ - I_{pt} \left[D_p - T_p\right]^+ \right. \\ \left. + \beta_{pq} \left[Q_p^{LB} - Q_p\right]^+ - I_{pq} \left[Q_p - Q_p^{LB}\right]^+ \right] \Bigg] \Bigg), \end{aligned} \tag{2}$$

$$\text{Max multiproject quality}\left(Q_p\right) = \alpha_p Q_{p,\,\min} + \left(1 - \alpha_p\right) Q_{p,avg}. \tag{3}$$

Objective function:

$$\text{minimize } z = \sum_{p \in P} \left[\left(\frac{T_p}{D_p} \times w_{pt} \right) + \left(\frac{C_p}{C_p^{UB}} \times w_{pc} \right) - \left(\frac{Q_p}{Q_p^{UB}} \times w_{pq} \right) \right]. \tag{4}$$

Subject to:

$$T_p \leqslant D_p, \tag{5}$$

$$C_p \leqslant C_p^{UB}, \tag{6}$$

$$\alpha_p Q_p^{\min} + \left(1 - \alpha_p\right) Q_p^{avg} \geqslant Q_p^{LB}, \tag{7}$$

$$S_{i(p)} + t_p^{im} \leqslant S_{j(p)} \quad p = 1, 2, \ldots, P; \; i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{8}$$

$$\sum_{i}\left(\frac{dc_{p}^{im}}{t_{p}^{im}}\right)X_{p}^{im}A_{imx(p)}\leqslant RU_{UB}\quad p=1,2,\ \ldots,\ P;\ \ i=1,2,\ \ldots,\ n;\ \ m=1,2,\ \ldots,\ M, \tag{9}$$

$$\mathrm{RR}_{k(p)}\leqslant\mathrm{RR}_{UB(k)(p)}\quad p=1,2,\ \ldots,\ P;\ \ k=1,2,\ldots,\ K, \tag{10}$$

$$\sum_{m\in M}X_{p}^{im}=1\quad p=1,2,\ \ldots,\ P;\ \ i=1,2,\ \ldots,\ n;\ \ m=1,2,\ \ldots,\ M, \tag{11}$$

$$t_{p}^{im}\geqslant 0\quad p=1,2,\ \ldots,\ P;\ \ i=1,2,\ \ldots,\ n;\ \ m=1,2,\ \ldots,\ M, \tag{12}$$

$$X_{p}^{im}\in\{0,1\}\quad p=1,2,\ \ldots,\ P;\ \ i=1,2,\ \ldots,\ n;\ \ m=1,2,\ \ldots,\ M, \tag{13}$$

$$x\in[0,T]. \tag{14}$$

The portfolio duration is calculated using Equation (1) by computing the maximum time taken by all the network paths of projects. The network path with the maximum time determines the portfolio duration. To satisfy resource constraints, the start time of each activity is taken as an optimization variable. The optimization algorithm determines the best start time for each activity such that each resource such as labor and equipment is within the available capacity. The total resource utilization at each time step should be less than the maximum value set by the user. The assumption involved is that the cost of the activity is distributed uniformly throughout the activity duration (Equation (9)). In Equation (2), the total portfolio cost is computed as the sum of direct, indirect and constraint violation costs of projects. The net quality of the portfolio is computed in Equation (3) as a combination of the minimum and average quality values among the selected activity modes of projects. The optimal solution obtained by minimizing the objective function (Equation (4)) contains the values of decision variables. The objective function is a weighted sum of normalized values of time, cost and quality. The optimization is executed multiple times with different combinations of weight factors in order to obtain many solutions that have different trade-offs among the three objectives. The resulting solutions are filtered according to the Pareto optimality criterion. The bounds for time, cost and quality in the constraints represented by Equations (5)–(7) are input by the user. This might be as per the contractual requirements (Monghasemi *et al.*, 2015; Mungle *et al.*, 2013) or from practical project management considerations. The precedence constraints are used to establish the sequence of activity implementation (Equation (8)). Constraint (Equation (10)) satisfies the renewable resource availability. Constraint (Equation (11)) guarantees the selection of only one mode for each activity. Constraints (Equations (12)–(13)) define the domain of variables. Constraint (Equation (14)) specifies the time step.

5. Evaluation–testing with modified MRCPSP data sets (PSPLIB)

Selected MRCPSP data sets from the PSPLIB are modified and used in this study, as shown in Figure 3. The data sets are modified to accommodate cost and quality aspects by using the relationships found in sample case study projects. A total of ten portfolio instances have been created for testing. For illustration, project no. 1 of the first instance is shown in Table II. Other projects of this instance, no. 2 and no. 3, can be found by following the URL link (https://shorturl.at/ixCEK). Data related to remaining portfolio instances are also available in the above link. Each project activity consists of three execution modes. The estimated total

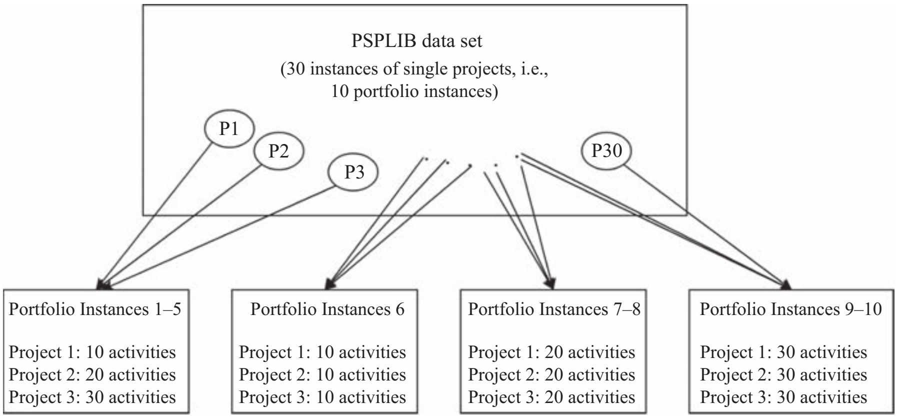


Figure 3. Creation of benchmark test data

number of combinations for the first instance are 3^{10}, 3^{20} and 3^{30}, where the exponent is the number of activities, and the base is the average number of execution modes. This indicates that the problem is exponentially complex and exhaustive search is not feasible.

The comparison of single-project approach and multi-project approach optimal solutions are tabulated in Table III for the instance no. 1. The single-project approach finds better solutions with respect to single or multiple objectives. Even though the single-project approach contains many variables considering all projects together; it has the advantage that the variation of maximum daily costs is shared among the projects. It helps to identify the schedules with the best project and portfolio performances compared to the multi-project approach solutions. A comparison of the remaining nine data sets can be found by following the URL link (http://bit.ly/2GlIraC). The single-project approach (portfolio optimization) solutions, i.e. activity execution modes, direct costs and resource utilization over time of all data sets can be found by following the URL link (http://bit.ly/2UHA8Ka). Portfolio constraint on maximum daily costs is considered in the next subsections.

5.1 Scenario 1: portfolio constraint on maximum daily costs

The project with MAXTWK regarding total cost is selected for rescheduling to absorb the over-assigned daily costs. The sensitivity-based compromise solution point is considered for rescheduling. The maximum daily portfolio cost is INR994,235. If the daily portfolio cost is limited to INR900,000, it is required to distribute the deviation (INR94,235) to any of the projects, and the selection is based on the heuristic priority rule, MAXTWK. Applying MAXTWK rule, Project no. 3 must be rescheduled (Table IV). A critical comparison of the multi-project approach and the single-project approach is given in Table V. The single-project approach finds a better solution compared to the multi-project approach under the constraint of maximum daily costs.

5.2 Scenario 2: portfolio constraint on maximum daily costs

Based on the MINLFT rule, the project with minimum finish time is rescheduled first. Therefore, Project no. 1 must be rescheduled to achieve portfolio maximum daily costs. The daily portfolio cost is INR994,235. If the daily portfolio cost is limited to INR900,000, it is required to distribute the deviation (INR94,235) to any of the projects, and the selection is based on the heuristic priority rules, MINLFT and MINSLK. Applying the priority rule, Project No. 1 must be rescheduled. A critical comparison of multi-project approach and

Table II. Modified MRCPSP-PSPLIB data set no. 1 – Project no. 1 (j103_10)

		Mode no. 1							Mode no. 2							Mode no. 3						
Act.	Pred.	R1	R2	N1	N2	T	C	Q	R1	R2	N1	N2	T	C	Q	R1	R2	N1	N2	T	C	Q
1		0	2	8	0	3	59,925	91.96	6	0	0	9	5	58,096	78.24	6	0	8	0	9	54,550	76.82
2		5	0	4	0	6	351,131	81.58	0	5	0	2	8	341,093	77.47	0	4	2	0	9	336,108	83.89
3		0	9	0	3	4	361,074	82.28	0	8	0	6	4	361,096	77.67	0	6	6	0	6	351,123	77.07
4	1,3	0	5	0	8	6	194,927	82.49	7	0	6	0	8	183,236	81.32	1	0	7	0	8	183,261	77.66
5	2	9	0	9	0	4	67,439	51.05	5	0	0	5	5	66,475	50.99	2	0	0	5	6	65,598	50.94
6	2	7	0	0	4	7	12,751	79.26	4	0	10	0	9	12,157	79.24	4	0	7	0	10	11,798	79.24
7	2	0	9	0	3	1	92,623	73.70	4	0	0	2	2	90,675	74.53	3	0	4	0	2	90,643	72.63
8	4,5,7	9	0	0	8	2	60,769	92.46	0	7	3	0	7	56,278	88.77	6	0	3	0	8	55,434	88.26
9	5,6	9	0	0	8	1	376,151	86.09	9	0	3	0	5	356,049	77.36	9	0	1	0	8	341,085	77.47
10	5,7	0	8	5	0	3	366,086	78.97	0	8	0	8	6	351,048	77.06	0	6	0	7	10	331,050	82.48

Notes: Max duration (due) in days = 14; max costs (budget in INR) = 2,000,000; min quality (conformance) in percent = 75; penalty rate/day (INR) = 30,000; resource penalty = 5,000; bonus rate/day (INR) = 15,000; maximum daily costs (INR) = 200,000; relative importance index = 0.25; renewable and non-renewable resource limits (R1, R2, N1, N2) = (13, 8, 41, 43)

Table III. Comparison of single-project approach and multi-project approach optimal solutions (dataset#1)

Project	Performance parameters	Multi-project approach (each project optimized individually)			Single-project approach (portfolio optimization)			Comparison of single-project approach against multi-project approach
		T	C	Q	T	C	Q	
Project no. 1 (j103_10)	Min time (d)	*16*	2,349,296	71.27	*14*	2,220,789	72.67	Improvement in time (13%)
	Min cost (INR)	16	*2,336,041*	71.36	14	*2,207,108*	72.71	Improvement in cost (6%)
	Max quality (%)	25	2,647,951	*72.12*	23	2,548,425	*73.16*	Improvement in quality (1.42%)
	Default RR-Pareto filtering (multi-objective compromise solution)	17	2,344,734	71.75	14	2,216,546	72.81	Improvement in time (18%), cost (5%), quality (1.46%)
	Sensitivity (multi-objective compromise solution): 3 days, 40,000 costs, 1% quality	16	2,336,041	71.36	14	2,207,487	72.73	Improvement in time (13%), cost (6%), quality (1.88%)
Project no. 2 (j209_8)	Min time (d)	*32*	4,634,291	69.60	*17*	3,900,341	69.92	Improvement in time (47%)
	Min cost (INR)	32	*4,634,291*	69.60	17	*3,900,341*	69.92	Improvement in cost (16%)
	Max quality (%)	47	5,448,514	*70.19*	54	5,829,383	*70.70*	Improvement in quality (0.72%)
	Default RR-Pareto filtering (multi-objective compromise solution)	32	4,700,886	69.73	17	3,900,341	69.92	Improvement in time (47%), cost (17%), quality (0.27%)
	Sensitivity (multi-objective compromise solution): 5 days, 50,000 costs, 1% quality	32	4,700,886	69.73	17	3,900,341	69.92	Improvement in time (47%), cost (17%), quality (0.27%)
Project no. 3 (j309_10)	Min time (d)	*33*	6,164,874	70.54	*30*	5,936,583	71.60	Improvement in time (9%)
	Min cost (INR)	33	*6,164,874*	70.54	30	*5,936,583*	71.60	Improvement in cost (4%)
	Max quality (%)	41	6,605,131	*70.84*	31	5,996,956	*71.65*	Improvement in quality (1.13%)
	Default RR-Pareto filtering (multi-objective compromise solution)	33	6,164,874	70.54	30	5,936,583	71.60	Improvement in time (9%), cost (4%), quality (1.48%)
	Sensitivity (multi-objective compromise solution): 5 days, 100,000 costs, 1% quality	33	6,164,874	70.54	30	5,946,583	71.60	Improvement in time (9%), cost (4%), quality (1.48%)

single-project approach found (http://bit.ly/2GlIraC). Single-project approach finds a better solution compared to a multi-project approach under the constraint of maximum daily costs.

6. Validation–testing with case study projects

Three building construction projects are used to demonstrate the effectiveness of the proposed approach (Kannimuthu *et al.*, 2019). The projects X, Y and Z have 32, 28 and 18 activities, respectively. These projects data can be found by following the URL link (https://bit.ly/2To6TMh). The estimated total number of combinations are 14.91^{32}, 18.61^{28} and 18.61^{18}, where the exponent is the number of activities, and the base is the average number of execution modes for each activity. This indicates that the problem is exponentially complex and exhaustive search is not feasible. Similar comparison (Table III) of multi-project approach and single-project approach optimal solutions for case study projects found by following the URL link (http://bit.ly/2Xq52ZM). The single-project approach (portfolio optimization) solutions, i.e., activity execution modes, direct costs and resource utilization over time can be found by following the URL link (https://bit.ly/2RiQ43m). Portfolio constraint on maximum daily costs is considered in the next subsections.

6.1 Scenario 1: Portfolio constraint on maximum daily costs

The project with MAXTWK regarding the maximum total cost is selected for rescheduling to absorb the over-assigned maximum daily costs. The sensitivity-based compromise

Table IV. Selection of project based on a heuristic priority rule

Priority rule	Project no. 1 (j103_10)	Project no. 2 (j209_8)	Project no. 3 (j309_10)	Daily costs (Portfolio)	Decision
MAXTWK (total costs)	2,336,041	4,700,886	6,164,874	(376,151 + 242,017 + 249,658 = 867,826)	Suggest Project no. 3 must be rescheduled (⩽281,832)

Table V. Comparison of rescheduled solutions based on the multi-project approach (priority rule) and single-project approach (max daily costs at the portfolio INR900,000)

Project information	Project performances	Multi-project approach (each project optimized individually – priority rule)	Single-project approach (portfolio optimization)	Comparison of single-project approach against the multi-project approach
Project no. 1 (j103_10)	Time (d)	16	14	Improvement in time (13%), cost (5%), and quality (1.99%)
	Min cost (INR)	2,336,041	2,216,546	
	Quality (%)	71.36	72.81	
Project no. 2 (j209_8)	Time (d)	32	18	Improvement in time (44%), cost (16%), and quality (0.19%)
	Min cost (INR)	4,700,886	3,961,024	
	Quality (%)	69.73	69.86	
Project no. 3 (j309_10)	Min time (d)	41	31	Improvement in time (24%), cost (9%), and quality (1.13%)
	Min cost (INR)	6,605,131	5,996,956	
	Max quality (%)	70.84	71.65	
Portfolio daily costs	900,000	867,826	599,549	The single-project approach identifies improvement over max portfolio daily costs (33.38%), a multi-project approach (30.91%)

solution point is considered for rescheduling. The daily portfolio cost is INR383,402. If the daily portfolio cost is limited to INR350,000, it is required to distribute the deviation (INR33,402) to any of the projects, and the selection is based on MAXTWK rule. Applying MAXTWK rule, Project X must be rescheduled. A critical comparison of multi-project approach and single-project approach found by following the URL link (http://bit.ly/2Vf0WBz). Single-project approach finds a better solution compared to a multi-project approach under the constraint of maximum daily costs at the portfolio level.

6.2 Scenario 2: portfolio constraint on maximum daily costs

Based on MINLFT rule, the project with minimum finish time is rescheduled first considering sensitivity based multi-objective compromise solution. Therefore, Project Z must be rescheduled to achieve portfolio maximum daily costs. The daily portfolio cost is INR383,402. If the daily portfolio cost is limited to INR350,000, it is required to distribute the deviation (INR33,402) to any of the projects, and the selection is based on the heuristic priority, MINLFT and MINSLK. Applying the priority rule, Project Z must be rescheduled. It can absorb only INR2,802. Therefore, the next immediate project, i.e., Project Y must reschedule to absorb INR30,600. It can also absorb only INR29,374. Thus, Project X must be rescheduled. A critical comparison of multi-project approach and single-project approach found by following the URL link (http://bit.ly/2Vf0WBz). Single-project approach finds a better solution compared to a multi-project approach under the constraint of maximum daily costs at the portfolio level.

7. Discussion

The results of the two approaches show significant differences when the resources are constrained in terms of the maximum daily costs of the portfolio. Figure 4 shows the advantages of finding minimum time through the single-project approach compared to the multi-project approach for the modified benchmark data sets. Similar inference is obtained from the sample case study projects, which can be found by following the URL link (http://bit.ly/2Vhc2WF). The single-project approach solutions are shown to be better both in the cases of single objectives and multiple objectives, for different settings, such as, whether to use the default RR-Pareto method or the sensitivity-based filtering.

Identical or better solutions have been obtained through portfolio optimization for the sample case study projects when the objective is to minimize costs and maximize quality, using the default RR-Pareto filtering, and the sensitivity-based filtering. Details are

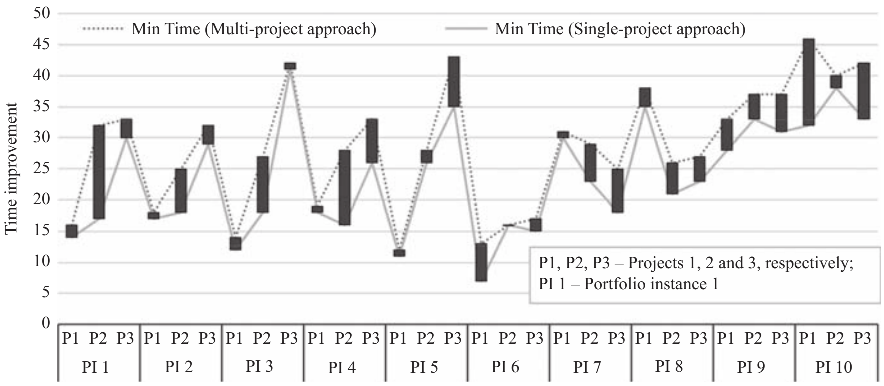


Figure 4. Comparison of single-project approach and multi-project approach for minimum time – modified benchmark data sets

available in the above URL link. When the heuristic priority rule, MAXTWK is used to meet portfolio constraints in the multi-project approach, more constrained projects attract resources from less constrained projects, resulting in overall low performance. The single-project approach also shows significant advantage compared to the multi-project approach when MINLFT and MINSLK heuristics are used (http://bit.ly/2Vhc2WF). The single-project approach is superior when the resources are constrained, which replicates the realistic environment of a construction organization.

The following inferences are made using the evaluation and validation cases:

- Sharing of constrained (limited) resources with multiple projects is required to maximize resource utilization and also to meet the projects' needs (Liu and Lu, 2019). The single-project approach reveals the importance of sharing renewable resources among the multiple concurrent projects to achieve better project performances in terms of time, cost and quality. Whereas in the multi-project approach, limited sharing of resource is possible because each project has only partial information about the other projects.
- The time at which the resources could be shared with other projects to enhance portfolio performance is available in the single-project approach. It enables coordination among the project personnel.
- The optimization algorithm is able to find solutions within cash-flow constraints, in terms of maximum daily cost constraint. The mathematical model considers penalty and bonus of all the projects in the portfolio in order to assign constrained resources to each project.

8. Summary and conclusions

Multi-project scheduling under a resource-constrained environment is a challenging task for any construction company. It is evident that companies work in a resource-constrained setting, striving to achieve compromises among the multiple conflicting objectives of time, cost and quality in a multi-project environment. In the resource-constrained state, it is possible to change activity execution modes by altering the construction method, materials and crew sizes. Different combinations of these can provide many possible ways to complete the activities with different time, cost and quality values. This paper proposes a framework for identifying the best combination of activity execution modes for achieving the objectives and satisfying the constraints in a multi-project environment. In the proposed framework, an MRCMPSP is formulated and solved using multi-objective optimization. The framework is evaluated using modified benchmark data sets of MRCPSPs from the PSPLIB. The framework is also validated using actual construction projects. Using this framework, the effectiveness of the single-project approach (portfolio optimization) is compared with the multi-project approach (projects are optimized individually). The conclusions are the following:

- in a multi-project environment, the single-project approach generates better schedules than the multi-project approach.
- The single-project approach permits resources to be shared effectively among projects and results in better performance when the resources are constrained.
- Heuristics proposed in the multi-project approach are not efficient in reducing the maximum daily costs to acceptable limits.

Contributions of this paper are: formulation of a new mathematical model for optimizing multiple objectives in a multi-project environment considering explicit resource constraints and daily cost restrictions at the portfolio level; and demonstration of new techniques for identifying compromise solutions for the MRCMPSP. The framework proposed in this paper provides construction and portfolio planners to make managerial decisions under constrained resource situations in a multi-project setting. This framework could be further extended by incorporating other aspects, such as resource transfer time and cost.

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