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Optimizing time, cost and quality in multi-mode resource-constrained project scheduling

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Abstract

Purpose – The purpose of this paper is to develop a framework to optimize time, cost and quality in a multi-mode resource-constrained project scheduling environment.

Design/methodology/approach – A case study approach identified the activity execution modes in building construction projects in India to support multi-mode resource-constrained project scheduling. The data required to compute time, cost and quality of each activity are compiled from real construction projects. A binary integer-programming model has been developed to perform multi-objective optimization and identify Pareto optimal solutions. The RR-PARETO3 algorithm was used to identify the best compromise trade-off solutions. The effectiveness of the proposed framework is demonstrated through sample case study projects.

Findings – Results show that good compromise solutions are obtained through multi-objective optimization of time, cost and quality.

Research limitations/implications – Case study data sets were collected only from eight building construction projects in India.

Practical implications – It is feasible to adopt multi-objective optimization in practical construction projects using time, cost and quality as the objectives; Pareto surfaces help to quantify relationships among time, cost and quality. It is shown that cost can be reduced by increasing the duration, and quality can be improved only by increasing the cost.

Originality/value – The use of different activity execution modes compiled from multiple projects in optimization is illustrated, and good compromise solutions for the multi-mode resource-constrained project scheduling problems using multi-objective optimization are identified.

Keywords Multi-objective optimization, Global optimization,
Construction quality assessment system (CONQUAS), Multi-criterion decision-making,
Multi-mode resource-constrained project scheduling, Time–cost–quality

Paper type Research paper

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1. Introduction

Traditional scheduling techniques, such as the critical path method and the program evaluation and review technique, assume unlimited availability of resources (Goncalves *et al.*, 2008). However, in practice, construction firms work in a limited resource environment. Mathematical approaches to accommodate resource utilization in project schedules include resource allocation and resource leveling. Many authors use the terms, resource allocation and resource-constrained project scheduling problem (RCPSP) interchangeably (Hegazy, 1999). RCPSP is defined as scheduling of activities under precedence and resources constraints to minimize the project duration (Hartmann and Briskorn, 2010). In multi-mode resource-constrained project scheduling problem (MRCPSP), each activity can be executed in one of several possible modes, each mode having a distinct relationship between the resources used and the duration of the activity. The objective is to minimize the project duration (Mika *et al.*, 2015). The different activity execution modes involve different combinations of construction methods, materials and crew sizes (El-Rayes and Kandil, 2005; Zhang and Xing, 2010). Resource leveling is described as reducing the resource fluctuation without extending the project duration under unlimited resource conditions (Leu and Yang, 1999).

While the traditional formulations of RCPSP and MRCPSP deal with a single objective (duration), other objectives, such as cost and quality, should not be ignored (Xu and Zeng, 2015). These objectives often conflict with each other. The trade-offs among conflicting objectives have been considered by some researchers to identify acceptable project schedules (Cheng *et al.*, 2015; Leu and Yang, 1999). The overall project performance depends on the relationship between the allocated amount of resources and the duration of activities (Mika *et al.*, 2015). The resource–duration relationship can be either discrete or continuous. The discrete case arises from the possibility to execute activities in different distinct modes, such as using specific equipment. The continuous case typically involves resources whose quantities are real numbers and can be considered as the case of infinite modes (Kannimuthu *et al.*, 2018; Kao *et al.*, 2006).

In practice, decision making in the presence of multiple objectives is complex. The acceptable trade-off among multiple objectives is of paramount importance to identify the ways to execute and complete the projects in challenging environments. On the one hand, the contractors must deliver good quality work to survive in the competitive market (Kong *et al.*, 1997). Resources that improve productivity may save time but increase cost. On the other hand, the reduction in either time or cost mostly decreases the quality of the project (Cheng *et al.*, 2015). A major challenge in the mathematical modeling of the time–cost–quality optimization problem is developing an expression to evaluate the expected quality of a given schedule. Project manager and client must jointly determine the rules by which subjective quality criteria are measured and aggregated (Pollack-Johnson and Liberatore, 2006). Many developed countries use standard checklists to measure the activity quality in terms of efficiency of workmanship (Jhun *et al.*, 2015). While these schemes are designed to evaluate the quality of construction work that has already been completed, these have not been used in optimization, which requires a method to predict the quality that might be achieved by executing a specified sequence of activities.

The primary aim of this research is to develop a systematic approach to handle time, cost and quality objectives in multi-mode resource-constrained scheduling. Each project activity could be executed in multiple modes, and the goal is to select the optimal combination of modes of activities such that acceptable trade-off is achieved among the three objectives. The research question is:

RQ1. How the selection of activity execution mode influences the project performance parameters.

The paper is organized as follows: Section 2 reviews literature related to time–cost–quality trade-off problems. The methodology developed in this research is presented in Section 3. A mathematical model formulated for optimizing multiple objectives to achieve the trade-offs in MRCPSP is shown in Section 4. Quantification of construction quality of activities and identification of activity execution modes are detailed in Sections 5 and 6, respectively. In Section 7, the model validation is described. Finally, Section 8 contains the results and possible future research directions.

2. Approaches to solve time–cost–quality trade-off problems

The RCPSP is NP-hard (Hartmann and Briskorn, 2010). Broadly, two solution approaches have been applied to solve the project scheduling problems: exact and approximate. Exact methods have high computational complexity due to a combinatorial explosion of the number of possible solutions (Senouci and Eldin, 2004). Approximate methods make use of heuristics. Heuristic methods can handle complex problems and are extensively used in practice. Heuristics are problem dependent, implying that the rules are specific to a model and cannot be equally applied to all the problems. They do not guarantee an optimal solution (Leu *et al.*, 2000). Meta-heuristics provide a generalized and robust approach to offset the limitations imposed in exact and heuristic methods. Nevertheless, it cannot guarantee an optimal solution either.

One approach to treat multiple objectives is to optimize only one objective at a time while setting bounds on the others (Babu and Suresh, 1996; Khang and Myint, 1999; Raphael and Smith, 2003). Another common approach is to generate a Pareto front, which consists of a set of non-dominated solutions that are obtained through Pareto filtering of all the generated solutions. During Pareto filtering, a solution S_i is accepted only if no solution S_j exists that is better than S_i with respect to all the criteria. In this approach, the solution to the multi-objective optimization problem is a set of feasible alternatives that represent different levels of trade-offs among the objectives.

Fuzzy clustering genetic algorithm (FCGA) was used to obtain Pareto surfaces of time–cost–quality (Mungle *et al.*, 2013). Khalili-Damghani *et al.* (2015) and Tavana *et al.* (2014) generated multiple activity execution modes, to solve the discrete time–cost–quality trade-off problem. Monghasemi *et al.* (2015) proposed an evidential reasoning (ER) to identify the best Pareto solution for multiple objectives. Reza-Pour and Khalili-Damghani (2017) used stochastic chance constraint programming (SCCP) and goal programming (GP) to handle the uncertain nature and multiple objectives of time, cost and quality. Earlier studies on time–cost–quality trade-off problems are shown in Table I.

All the above work based on the concept of Pareto optimality stop at generating a set of non-dominated solutions. Not much attention has been paid to the problem of selecting the best compromise solution from the Pareto set. An algorithm called Relaxed-Restricted Pareto filtering (RR-PARETO3) has been proposed for solving this problem (Raphael, 2011). The default RR-PARETO3 algorithm iteratively removes the worst solutions according to each objective, starting with the most important objective. The process stops when a single solution remains in the set. This solution represents the best compromise among all the objectives. This algorithm has so far not been used in time–cost–quality optimization.

An important issue is how quality can be incorporated in the optimization model. Quality performance indicators were used to quantify the activity quality in time–cost–quality trade-off problem for highway construction (El-Rayes and Kandil, 2005). Tareghian and Taheri (2006, 2007) formulated integer programming to maximize the project quality while minimizing the total costs and deadline. Pollack-Johnson and Liberatore (2006) quantified the activity quality with analytic hierarchy process (AHP) to optimize time, cost, minimal and medium quality. Kim *et al.* (2012) formulated a mixed integer linear programming to minimize the potential quality loss cost due to the excessive crashing of activities.

Table I.
Review of earlier studies on time–cost–quality trade-off

Author (yr.)	Activity mode Dual/multiple	Modeling approach	Objective	Solution approach/method
Babu and Suresh (1996)	Dual	LP	Optimizing one entity by assigning bounds on other two	No details
Khang and Myint (1999)	Dual	LP	Examining the efficiency of Babu and Suresh (1996) method	No details
El-Rayes and Kandil (2005)	Multi-mode	LP	Quantifying the quality with indices for calculating project quality to optimize time, cost and quality	GA
Tareghian and Taheri (2006)	Multi-mode (generator)	IP	Investigating different forms of quality aggregations and time–cost–quality trade-off	No details
Pollack-Johnson and Liberatore (2006)	Multi-mode	GP–MILP	AHP to quantify the quality of activity with the objective time, cost, minimal and medium quality	No details
Tareghian and Taheri (2007)	Multi-mode (generator)	IP	Maximizing project quality while minimizing total costs and the deadline	Electromagnetic scatter search
Kim *et al.* (2012)	Dual	MILP–PQLC	Minimizing the potential quality loss cost due to the excessive crashing of activities	No details
Mungle *et al.* (2013)	Multi-mode	MIP	Obtaining the better Pareto boundaries to time–cost–quality trade-off problem	FCGA
Tavana *et al.* (2014)	Multi-mode (simulation)	MINLP	Solving discrete time–cost–quality trade-off	NSGA II, EEC
Monghasemi *et al.* (2015)	Multi-mode	MIP	Minimizing project duration and cost, and maximizing project quality	ER, MOGA
Khalili-Damghani *et al.* (2015)	Multi-mode (generator)	MIP	Solving the discrete GPRs multi-objective multi-mode TCQTPs	DSAMOPSO
Reza-Pour and Khalili-Damghani (2017)	Multi-mode	SCCP, GP	Stochastic time–cost–quality trade-off project scheduling problem	No details

Existing works in the area of time–cost–quality optimization have assumed hypothetical data to model quality. The activity quality values were either generated randomly (Tavana *et al.*, 2014) or through a higher level of quality performance indicators (El-Rayes and Kandil, 2005). Quality has never been estimated using real data from projects for use in optimization. Even though the quality estimation of activities through a checklist of standards is still prevalent in many countries, this approach has not been used in the mathematical optimization of the project schedule.

Another limitation of most existing work is that hypothetical activity execution modes have been used (Monghasemi *et al.*, 2015; Mungle *et al.*, 2013). Tran *et al.* (2015) demonstrated the ability to optimize time, cost and quality using a case study, however, it is not clear how time, cost and quality are estimated for each activity mode in the project. The activity execution modes are randomly generated in the study of Khalili-Damghani *et al.* (2015). Dual mode (Kim *et al.*, 2012) and multi-mode (Monghasemi *et al.*, 2015) problems have been studied under hypothetical conditions or using test instances (Khalili-Damghani *et al.*, 2015). Case studies have been used in the studies of Cheng *et al.* (2015) and El-Rayes and Kandil (2005) for studying time–cost trade-off. These have been expanded to accommodate the quality aspect by modifying the source case by Feng *et al.* (1997). However, it is not clear how the activity execution modes have been obtained in the case study and whether these data are realistic. The mathematical models in earlier studies (Monghasemi *et al.*, 2015; Mungle *et al.*, 2013) have not explicitly included costs due to the quality violation. The consideration of costs due to the quality violation is important as many previous studies have reported (Mahmood *et al.*, 2014). None of the above studies seems to have used quality data based on real construction projects.

In summary, the point of departure from previous research involves the following:

1. development of a methodology for using past data from real construction projects to predict the expected quality of a given schedule;
2. identification of activity execution modes from real construction projects and using these data for multi-objective optimization of time, cost and quality in the planning and scheduling of similar new projects;
3. formulation of a new mathematical model for achieving the trade-offs among time, cost and quality; and
4. testing and adoption of new multi-objective optimization approaches to resource allocation and trade-off problems.

3. The stages of the proposed framework

The proposed framework for optimizing multi-mode RCPSP consists of four stages:

- Stage 1: formulation of the mathematical model – an integer-programming model is developed to optimize the multiple objectives of time, cost and quality. The details of the mathematical model are in Section 4.
- Stage 2: quantification of construction quality of activities – construction quality assessment system based on CONQUAS framework of Singapore (BCA Singapore, 2017) is used to evaluate the quality performance scores for construction activities (see Section 5). Quality of each activity is estimated from the sum of its element performance indicators using a checklist of standards. Finally, the project quality is calculated from the relative importance of minimum and average quality parameters.
- Stage 3: identification of different activity execution modes – each activity can be executed in different modes. The modes vary in the combination of construction methods, materials and crew sizes (El-Rayes and Kandil, 2005). For each activity in the work breakdown structure of the project, possible modes should be identified. This can be done by compiling data from previous projects. To illustrate this procedure, daily progress data collection, site visits and surveys were done in this research from eight construction projects. Activity execution modes, as well as their performance parameters, were collected. If a database of such information is developed for a company or a country, it could be used in the optimization of the project schedule for similar kinds of projects.
- Stage 4: solving the optimization model – once the optimization model is formulated mathematically, an appropriate algorithm should be used to find the solutions. This involves two steps. First, a set of non-dominated solutions (Pareto front) is generated using a multi-objective optimization algorithm. Second, a compromise solution is identified by specifying acceptable trade-offs among conflicting objectives.

In this stage, 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. PGSL has several advantages over genetic algorithm (GA) and simulated annealing (SA); it has been shown to perform better when the number of variables increases (Raphael and Smith, 2005). Even though the core PGSL algorithm is meant to solve single-objective optimization problems, it can be used to generate the Pareto front by taking a weighted sum of objectives as the cost function and repeating the optimization multiple times using a different combination of weight factors. All the solutions generated during the process are filtered according to the criterion of Pareto optimality.

After generating the Pareto front, a single solution needs to be selected from the set of non-dominated solutions. In many problems, this selection is left to the user. In this research, an algorithm called RR-PARETO3 (Raphael, 2011) is used. In this algorithm, the best compromise solution is chosen based on the order of the objectives according to their importance and the sensitivity of each objective. It is emphasized that weight factors are not used to combine the values of individual objectives into a single number. Instead, worst solutions according to each criterion are iteratively filtered out until a single solution is obtained.

4. Formulation of mathematical model

Consider a project 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. Then a compromise trade-off solution is obtained by using the RR-PARETO3 algorithm. The project duration is estimated by identifying the path with maximum duration. 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. Finally, the quality of activity is calculated based on the construction quality assessment system considering the relative importance of minimum and average quality of the activities.

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; and
- identified activity execution modes apply to similar kinds of projects.

The indices and input parameters:

- n: set of project activities, $i \in n$.
- 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_{UB}: upper-bound of the project cost.
- Q_{LB}: lower-bound of the project quality.
- Q_{UB}: upper-bound of the project quality (100 percent).
- D: contractual due date of the project.
- t_i^m: duration of activity i in mode m.

- C_1: direct and indirect costs.
- C_2: costs of constraint violation.
- dc_i^m: direct cost of activity i in mode m.
- ic: indirect cost of the project per period.
- βt, βq: penalty for time and quality constraint violation, respectively.
- It, Iq: bonus for early completion and quality satisfaction, respectively.
- w_t, w_c, w_q: weight of time, cost and quality objective, respectively.
- Q_{ie}^m: quality performance of activity i of element e in mode m.
- Q_i^m: quality of activity i in mode $m = \sum_{e \in E} Q_{ie}^m$.
- $Q_{\min}$: minimum quality among the selected activity modes.
- Q_{avg}: average quality among the selected activity modes.
- α: relative importance between the minimum and average quality.
- x: auxiliary variable that represents a time step in the range [0, T].
- $A_{i,m,x}$: 1 if activity i is performed in mode m at time step x, that is, if $S_i \leqslant x < \left(S_i + t_i^m\right)$, 0 otherwise.
- RUx: resource utilization (direct costs) at time step x: $\left(\sum_i \left(dc_i^m / t_i^m\right) X_i^m A_{i,m,x}\right)$.
- RU_{UB}: upper-bound of the maximum daily resource utilization (direct costs).

Decision variable:

- X_i^m: 1 if activity i executed in mode m, 0 otherwise.
- S_i: start time of activity i.

Mathematical model:

$$\text{Minimize project duration } (T) = \max_{L_p \in L} \max_{i \in n} \left(\sum_{m \in M} \left(S_i + t_i^m\right) X_i^m \right), \tag{1}$$

$$\begin{aligned} \text{Minimize project cost } (C) &= C_1 + C_2 \\ &= \left[\left(\sum_{i \in n} \sum_{m \in M} dc_i^m X_i^m \right) + (ic \times T) \right] + \left[\beta_t [T - D]^+ \right. \\ &\quad \left. - I_t [D - T]^+ + \beta_q [Q_{LB} - Q]^+ - I_q [Q - Q_{LB}]^+ \right], \end{aligned} \tag{2}$$

$$\text{Maximize project quality } (Q) = \alpha Q_{\min} + (1 - \alpha) Q_{\text{avg}}. \tag{3}$$

Objective function:

$$\text{minimize } z = \left(\left(\frac{T}{D} \times w_t \right) + \left(\frac{C}{C_{UB}} \times w_c \right) - \left(\frac{Q}{Q_{UB}} \times w_q \right) \right), \tag{4}$$

Subject to:

$$T \leqslant D, \tag{5}$$

$$C \leqslant C_{UB}, \tag{6}$$

$$\alpha Q_{\min} + (1-\alpha) Q_{\text{avg}} \geqslant Q_{LB}, \tag{7}$$

$$S_i + t_i^m \leqslant S_j, \text{ where } i \text{ is a preceding activity of } j, i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{8}$$

$$\sum\nolimits_i \left(\frac{dc_i^m}{t_i^m} \right) X_i^m A_{i,m,x} \leqslant RU_{UB} \; i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{9}$$

$$\sum\nolimits_{m \in M} X_i^m = 1 \; i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{10}$$

$$t_i^m \geqslant 0 \; i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{11}$$

$$X_i^m \in \{0, 1\} \; i = 1, 2, \ldots, n; \; m = 1, 2, \ldots, M, \tag{12}$$

$$x \in [0, T]. \tag{13}$$

The project duration is computed using Equation (1) by calculating the maximum time taken by all the network paths. A network path Lp consists of a sequence of activities starting from the beginning of the project to the end of the project. When some activities are executed in parallel, there will be multiple network paths having different values for the total time of activities. The network path with the maximum time is the critical path and determines the project duration. In order to satisfy resource constraints, the start time of each activity is taken as an optimization variable. Theoretically, it is possible to use a single type of decision variable of the form $X_{i,m,t}$. This can represent the condition that activities could start at any time (after the completion of a preceding activity). However, this formulation is not very efficient because it increases the number of decision variables. Instead, in our formulation, the start time of each activity is taken as the decision variable. This will reduce the number of decision variables and search will be more efficient. $A_{i,m,x}$ is a secondary variable computed using the values of start time and activity duration.The optimization algorithm determines the best start time for each activity such that the total resource utilization at each time step is less than the maximum value set by the user. In general, an upper-bound could be set for each resource used in the project such as labor and equipment. However, in this paper, the only resource considered is the cost, the equivalent daily cost of all the equipment and other resources is computed in order to check the resource constraint. The assumption involved is that the cost of the activity is distributed uniformly over the time period of the activity and that total resource utilization at each time step is indirectly represented by the direct cost of activities scheduled at this time (Equation (9)). In Equation (2), the cost is computed as the sum of direct, indirect and constraint violation and bonus costs. The quality is computed in Equation (3) as a combination of the minimum and average quality values among the selected activity modes. The optimal solution obtained by minimizing the objective function (Equation (4)) contains the values of decision variables, that is, which modes are selected for each activity and its starting time. The objective function is a weighted sum of normalized values of time, cost and quality. Normalization is done because each objective has different units and scale. The limiting values 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 arrive at possible network paths and are therefore explicitly represented in the model (Equation (8)). Constraint (Equation (10)) guarantees the selection of only one mode for each activity. Constraints Equations (11) and (12) define the domain of variables. Constraint (Equation (13)) defines the time step.

5. Quantification of construction quality of activities

Many countries have introduced quality assurance and assessment schemes to ensure the quality of building projects and ultimately, the construction industry. Quality assessment frameworks of three nations were studied to select an appropriate system for a prototype implementation: Singapore (construction quality assessment system (CONQUAS)), Hong Kong (performance assessment scoring system (PASS)) and Malaysia (quality assessment system in construction (QLASSIC)). CONQUAS model is chosen because it is the base model for other frameworks, the scope of work considered in this study is limited to structural (formwork, rebar, concreting) and architectural components (block work, plastering, painting and flooring) which are common in all the frameworks, this model (architecture scheme) is adopted by the Construction Industry Development Council, India even though, it is yet to attain wider awareness (Marimuthu *et al.*, 2018; Ong *et al.*, 2018).

The example of CONQUAS-based formwork activity elements and standards are mentioned below. The three broad terms have been used to estimate the activity quality, such as item, elements and standards. The term item represents the activity (e.g. formwork), the term elements represent the parameters involved in the activity and finally, the term standards represents a set of conditions to be satisfied by the element. Delphi method was carried out to get a consensus on the importance of quality elements and standards from construction professionals, which are used to calculate the activity quality during the identification of different activity execution modes (Sawhney *et al.*, 2014). Convenience sampling method was adopted to select the respondent feedbacks on adopting CONQUAS framework. The activity quality is evaluated based on the number of standards (checklists) checked at the end of the day. For example, formwork activity has 11 standards as mentioned below. During the quality check (workmanship) at the end of the day, if all the standards pass then activity quality is set to be 100 percent. Otherwise, the percentage of passes will be considered to activity quality:

1. Element 1: formwork dimensions and openings for services:
    - Standard 1: tolerance for cross-sectional dimensions of cast-in-situ and precast elements: +10 mm/−5 mm.
    - Standard 2: tolerance for penetration/opening for services: +10 mm for size and ±25 mm for location.
    - Standard 3: tolerance for length of precast members (major dimension of unit):
        - up to 3 m: ±6 mm.
        - 3 m–4.5 m: ±9 mm.
        - 4.5 m–6 m: ±12 mm.
        - additional deviation for every subsequent 6 m: ±6 mm.

(2) Element 2: alignment, plumb and level:
   - Standard 1: tolerance for departure of any point from its position: 10 mm.
   - Standard 2: tolerance for plumb: 3 mm/m, maximum 20 mm.
   - Standard 3: maximum deviation of mean level of staircase thread to temporary benchmark: ±5 mm.
   - Standard 4: for cast-in-situ elements, the deviation of level of any point from the intended level: ±10 mm.

(3) Element 3: condition of formwork, props and bracing:
   - Standard 1: formwork must be free from defects.
   - Standard 2: before concreting, the interior must be free from debris.
   - Standard 3: all formwork joints must not have gaps to prevent leakage.
   - Standard 4: there must be adequate support, bracing and tie-back for the formwork to prevent bulging or displacement of structural elements:

$$\text{Quality of activity} = \text{sum of individual quality elements} = \sum\nolimits_{e \in E} Q_{ie}^{m}.$$

The quality scores are computed daily in the case studies of building projects. These data are used to calculate the average quality score for each activity that is executed in a particular mode. This is used to predict the expected quality of future projects during the optimization process. Earlier studies have used hypothetical quality scores in optimization. To the authors' knowledge, this is the first study that has used CONQUAS model-based quality data compiled from real projects in multi-criteria multi-mode project scheduling decision problem.

6. Identification of different activity execution modes

A crucial data that is needed for optimization are the list of different modes of execution of project activities and their performance parameters. In the absence of well-established databases, these data have to be collected from the field. To demonstrate that these data are available and it is feasible to perform optimization, a case study approach was adopted. Convenience sampling method was adopted to select the cases. Data were collected from eight building construction projects to determine practical activity execution modes for seven activities, namely, formwork, rebar/reinforcement, concreting, block work, plastering, painting and flooring. These projects involve the construction of buildings from 4 to 23 floors. The projects were completed within 12–48 months, costing INR 150 to 1,250m. Data were collected by interviewing project managers and obtaining project documents, such as the schedule, the bill of quantities and the daily progress report. The activity crew productivity is calculated for the different combinations of execution modes (Senarath Jayasinghe and Fernando, 2017). Alongside, quality assessment was also carried out to compute the quality parameter. Sampling approach is used to extract the relevant information. Rate analysis is carried out to identify the labor, material and equipment costs required to complete a unit of work. The collected data can be highly beneficial for a similar type of residential building construction projects and can also provide guidelines to other construction projects in terms of construction methods, materials and crew sizes. The activity execution modes for seven activities were identified from eight constriction projects are mentioned below:

(1) formwork: conventional, DOKA, MIVAN; plywood, steel, aluminum, crew size;

(2) rebar/reinforcement: cutting (manual/machine), bending (manual/machine) and shifting of rebar (manual/material hoist/tower crane), bar diameter ($<$ 18 mm, $>$ 18 mm), crew size;

(3) concreting: batching – machine batched and mixed, ready-mix concrete (RMC); shifting – manual, material hoist, tower crane, pump; different grades (M20, M25); different elements (beam and slab, wall and column); different levels (up to 5th level, above 5th level), crew size;

(4) block work: different blocks (aerocon blocks, solid blocks, clay burnt bricks with varied sizes); mortar type (readymade or site mix mortar); cement mortar ratio (1:5, 1:6); different sand sources (river sand, manufacturing sand, eco sand, combination); shifting (manual, material hoist, tower crane), crew size;

(5) plastering: manual, auto plaster, sprayer; mortar, gypsum; mortar ratio (1:4, 1:5); sand sources (river sand, manufactured sand, eco sand, combination), crew size;

(6) painting: whitewash with lime, satna lime, acrylic emulsion paint, putty, primer, crew size; and

(7) flooring: flooring (vitrified tile, mosaic tile, ceramic tile, granite, Kota stone, Italian marble); mortar ratio (1:5, 1:6); sand sources (river sand, manufactured sand, eco sand, combination), crew size.

For example, it was noted that plastering activity execution modes include the following: mortar application type – manual, auto plaster, sprayer; material type – cement mortar, gypsum; mortar ratios – 1:4, 1:5; sand sources – river sand, manufacturing sand, eco sand, combined and crew size. The first combination is manual mortar application with cement mortar of 1:4 ratio, river sand and a crew size of 3. The average crew productivity under this combination is found to be 13.23 sqm/day. The total quantity of work (100 sqm) to be done is extracted from the drawings, and the crew size is decided to achieve an acceptable duration. The duration required to complete the activity under this mode was found to be 2.52 days. However, it is round off to three days to complete the activity. Finally, the cost required to complete the work is estimated. The activity quality value is calculated from the average of daily quality following the construction quality assessment system standards.

7. Validation of the proposed framework

Three building construction project schedules are used to demonstrate the effectiveness of the proposed approach. These projects are located in Chennai, Bengaluru and Mangalore and were identified by convenience sampling. The projects are selected due to similar project type of activity execution modes involving residential building construction. The actual project names are withheld for confidentiality and are referred to as Project X, Project Y and Project Z. The data of Project X are tabulated in Table II. Data of Project Y and Project Z can be obtained by following the URL link (https://goo.gl/bJte6B). The project activity networks are shown in Figure 1. The following activities are considered in the schedule of the above projects for the construction of the first two floors: formwork, rebar/reinforcement, concreting, block work, plastering, painting and flooring. The projects X, Y, and Z have 32, 28 and 18 activities, respectively. The estimated total numbers of combinations of activity modes in the project networks are 6.03^{32}, 7.21^{28} and 6.61^{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.

The feasible solutions for Project X are tabulated in Table III. Solutions of Projects Y and Z can be obtained by following the URL link (https://goo.gl/uJAzU9). Pareto surfaces were

Table II.
Summary of activity execution modes for a sample case study X

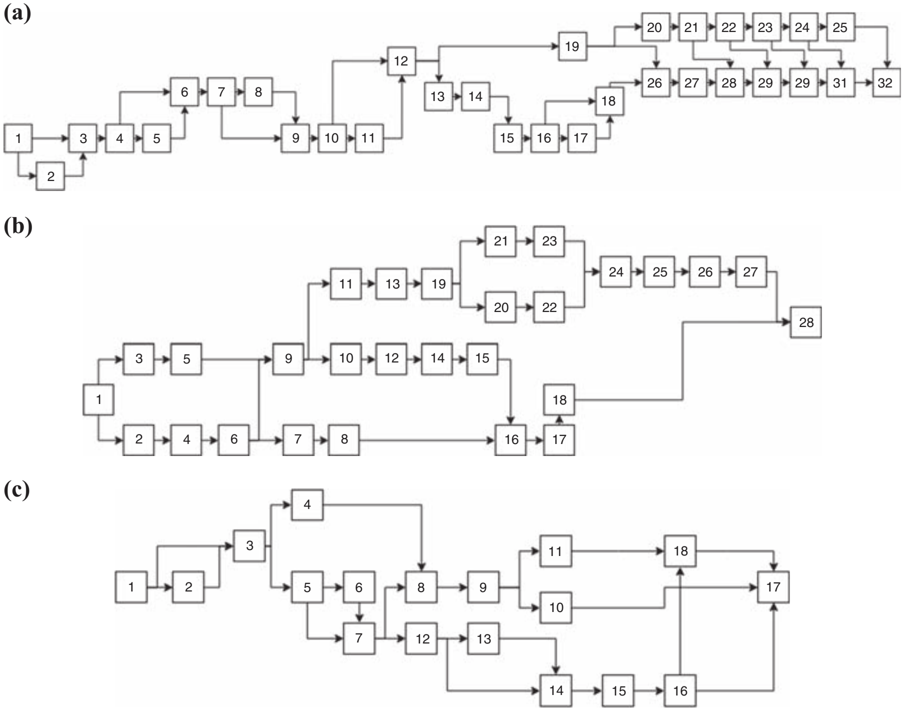
Activity	Pred	Mode1			Mode2			Mode3			Mode4		
		T	C	Q	T	C	Q	T	C	Q	T	C	Q
1. Basement – shuttering for shear wall or column	–	20	41,920	72.53	13	53,120	83.90	7	57,280	83.90	8	60,800	82.00
2. Basement – reinforcement for wall or column	1	9	404,141	79.02	7	406,925	79.02	10	403,162	80.23	11	402,365	79.16
3. Basement – concreting of shear wall or column	1, 2	13	286,910	78.12	9	365,885	79.95	5	367,835	79.95	3	369,330	79.95
4. Basement – shuttering for slab	3	20	54,000	74.63	16	58,000	81.86	14	65,600	78.01	10	64,800	87.03
5. Basement – reinforcement for slab	4	11	538,854	79.02	9	542,566	79.02	13	537,549	80.23	14	536,486	79.16
6. Basement – concreting slab	4, 5	14	308,980	78.12	7	320,110	78.12	10	369,740	81.27	5	372,050	81.27
7. 1st level – shuttering (wall and column)	6	17	35,370	72.53	11	44,820	83.90	6	48,330	83.90	7	51,300	82.00
8. 1st level – reinforcement (wall and column)	7	11	505,176	79.02	9	508,656	79.02	12	503,952	80.23	13	502,956	79.16
9. 1st level – concreting (wall and column)	7, 8	11	238,356	78.12	7	303,966	79.95	4	305,586	79.95	3	306,828	79.95
10. 1st level – shuttering (beam and slab)	9	18	48,600	74.63	14	52,200	81.86	12	59,040	78.01	9	58,320	87.03
11. 1st level – reinforcement (beam and slab)	10	11	505,176	79.02	9	508,656	79.02	12	503,952	80.23	13	502,956	79.16
12. 1st level – concreting (beam and slab)	10, 11	8	176,560	78.12	4	182,920	78.12	6	211,280	81.27	3	212,600	81.27
13. 2nd level – shuttering (wall and column)	12	16	32,750	72.53	10	41,500	83.90	5	44,750	83.90	6	47,500	82.00
14. 2nd level – reinforcement (wall and column)	13	12	589,372	79.02	10	593,432	79.02	14	587,944	80.23	15	586,782	79.16
15. 2nd level – concreting (wall and column)	14	12	264,840	78.12	8	337,740	79.95	4	339,540	79.95	3	340,920	79.95
16. 2nd level – shuttering (beam and slab)	15	19	49,950	74.63	15	53,650	81.86	13	60,680	78.01	10	59,940	87.03
17. 2nd level – reinforcement (beam and slab)	16	13	631,470	79.02	11	635,820	79.02	15	629,940	80.23	16	628,695	79.16
18. 2nd level – concreting (beam and slab)	16, 17	9	198,630	78.12	5	205,785	78.12	7	237,690	81.27	4	239,175	81.27
19. 1st level – block work	12	6	193,980	81.18	7	206,190	82.15	5	211,860	82.15	4	213,210	82.15
20. 1st level – plastering	19	8	63,900	74.11	13	57,900	75.42	9	61,200	75.42	13	59,400	72.43
21. 1st level – tile flooring	20	5	79,170	77.00	5	88,790	76.14	3	97,890	76.14	4	94,900	77.85
22. 1st level – putty – 2 coats	21	18	16,000	79.88	9	17,920	79.88						
23. 1st level – primer	22	9	11,840	77.85	5	12,800	77.85						
24. 1st level – first coat	23	6	14,400	83.64	10	12,160	82.62						
25. 1st level – final coat	24	6	14,400	83.64	10	12,160	82.62						
26. 2nd level – block work	18, 19	7	213,378	81.18	7	226,809	82.15	6	233,046	82.15	5	234,531	82.15
27. 2nd level – plastering	26	8	64,965	74.11	14	58,865	75.42	9	62,220	75.42	13	60,390	72.43
28. 2nd level – tile flooring	21, 27	5	76,125	77.00	5	85,375	76.14	3	94,125	76.14	4	91,250	77.85
29. 2nd level – putty – 2 coats	22, 28	18	15,500	79.88	9	17,360	79.88						
30. 2nd level – primer	23, 29	9	11,470	77.85	5	12,400	77.85						
31. 2nd level – first coat	24, 30	5	13,950	83.64	9	11,780	82.62						
32. 2nd level – final coat	25, 31	5	13,950	83.64	9	11,780	82.62						

(*continued*)

Table II.

Activity	Pred	Mode5			Mode6			Mode7			Mode8		
		T	C	Q	T	C	Q	T	C	Q	T	C	Q
1. Basement – shuttering for shear wall or column	–	6	65,600	82.00	23	39,680	76.16	8	57,280	83.89	6	62,080	83.89
2. Basement – reinforcement for wall or column	1	6	408,288	84.59	5	413,482	88.21	4	415,795	88.21	3	416,803	88.21
3. Basement – concreting of shear wall or column	1, 2	7	347,035	79.23	5	348,660	79.23	3	413,400	88.27	2	413,530	88.27
4. Basement – shuttering for slab	3	7	71,200	87.03									
5. Basement – reinforcement for slab	4	8	544,384	84.59	6	551,309	88.21	5	554,394	88.21	4	555,738	88.21
6. Basement – concreting slab	4, 5	4	374,290	81.27	5	348,460	84.29	2	441,630	86.43	2	443,100	86.43
7. 1st level – shuttering (wall and column)	6	5	55,350	82.00	19	33,480	76.16	7	48,330	83.89	5	52,380	83.89
8. 1st level – reinforcement (wall and column)	7	7	510,360	84.59	6	516,852	88.21	5	519,744	88.21	4	521,004	88.21
9. 1st level – concreting (wall and column)	7, 8	6	288,306	79.23	4	289,656	79.23	2	343,440	88.27	2	343,548	88.27
10. 1st level – shuttering (beam and slab)	9	6	64,080	87.03									
11. 1st level – reinforcement (beam and slab)	10	7	510,360	84.59	6	516,852	88.21	5	519,744	88.21	4	521,004	88.21
12. 1st level – concreting (beam and slab)	10, 11	2	213,880	81.27	3	199,120	84.29	1	252,360	86.43	1	253,200	86.43
13. 2nd level – shuttering (wall and column)	12	4	51,250	82.00	18	31,000	76.16	7	44,750	83.89	5	48,500	83.89
14. 2nd level – reinforcement (wall and column)	13	8	595,420	84.59	7	602,994	88.21	5	606,368	88.21	4	607,838	88.21
15. 2nd level – concreting (wall and column)	14	7	320,340	79.23	5	321,840	79.23	3	381,600	88.27	2	381,720	88.27
16. 2nd level – shuttering (beam and slab)	15	7	65,860	87.03									
17. 2nd level – reinforcement (beam and slab)	16	9	637,950	84.59	7	646,065	88.21	6	649,680	88.21	5	651,255	88.21
18. 2nd level – concreting (beam and slab)	16, 17	3	240,615	81.27	4	224,010	84.29	2	283,905	86.43	1	284,850	86.43
19. 1st level – block work	12	4	236,910	84.44	6	207,870	81.20	8	188,670	79.24	8	165,900	77.46
20. 1st level – plastering	19	9	62,700	72.43	6	69,600	86.41	4	75,600	88.78	15	53,100	80.60
21. 1st level – tile flooring	20	4	97,890	77.85									
22. 1st level – putty – 2 coats	21												
23. 1st level – primer	22												
24. 1st level – first coat	23												
25. 1st level – final coat	24												
26. 2nd level – block work	18, 19	4	260,601	84.44	6	228,657	81.20	9	207,537	79.24	9	182,490	77.46
27. 2nd level – plastering	26	9	63,745	72.43	6	70,760	86.41	4	76,860	88.78	15	53,985	80.60
28. 2nd level – tile flooring	21, 27	3	94,125	77.85									
29. 2nd level – putty – 2 coats	22, 28												
30. 2nd level – primer	23, 29												
31. 2nd level – first coat	24, 30												
32. 2nd level – final coat	25, 31												

Notes: Max duration (due) in days = 120; max costs (budget in Indian rupees) = 8,500,000; min quality (conformance) in percent = 70; penalty rate/day (Indian rupees) = 50,000; bonus rate/day (Indian rupees) = 30,000; max daily resource costs (Indian rupees) = 200,000; relative importance index (α) = 0.5



Notes: (a) Project X; (b) Project Y; and (c) Project Z

Figure 1.
Project network of sample case study projects

generated taking all the three objectives simultaneously. For ease of visualization, Pareto surfaces are plotted taking two objectives (Figure 2) and three objectives (Figure 3) separately. It should be noted that some Pareto optimal points get filtered out when one objective is ignored to generate Pareto plots. In all the three networks, the same trend is observed among Pareto optimal solutions: the cost can be reduced by increasing the project duration, and quality can be improved only at additional cost. The quantitative evidence is confirmed by the Pareto optimization using real case projects.

The best values of time, cost and quality obtained through single-objective optimization are tabulated in Table IV. The best compromise solution identified from the Pareto points through RR-PARETO3 filtering is also shown. In Project X, by increasing the total project duration by 13 days compared to its minimum project duration, a reduction in direct costs (1.61 percent) and an improvement in quality (3.31 percent) are achieved. Similarly, in Project Y, by increasing the total project duration by three days compared to its minimum project duration, a reduction in direct costs (3.44 percent) and a slight improvement in quality are achieved. Finally, in Project Z, by increasing the total project duration by six days compared to its minimum project duration, a significant reduction in direct costs (5.6 percent) and improvement in quality (2.70 percent) are achieved. It can be seen that a small increase in duration can achieve a considerable reduction in direct costs and a slight improvement in quality.

8. Summary and conclusions

Resource-constrained project scheduling is dominant in the construction industry since construction projects are executed mostly in a limited resource environment. With limited

Activity	Mode	Time (days)	Direct costs (Indian Rs)	Quality (%)	Early start	Late start	Opt start	Float
1	8	6	62,080	83.89	0	0	0	0
2	8	3	416,803	88.21	6	6	6	0
3	4	3	369,330	79.95	9	9	9	0
4	5	7	71,200	87.03	12	12	12	0
5	8	4	555,738	88.21	19	19	19	0
6	5	4	374,290	81.27	23	23	23	0
7	8	5	52,380	83.89	27	27	27	0
8	8	4	521,004	88.21	32	32	32	0
9	7	2	343,440	88.27	36	36	36	0
10	5	6	64,080	87.03	38	38	38	0
11	8	4	521,004	88.21	44	44	44	0
12	5	2	213,880	81.27	48	48	48	0
13	5	4	51,250	82	50	50	50	0
14	8	4	607,838	88.21	54	54	54	0
15	8	2	381,720	88.27	58	58	58	0
16	5	7	65,860	87.03	60	60	60	0
17	5	9	637,950	84.59	67	67	67	0
18	2	5	205,785	78.12	76	76	76	0
19	7	8	188,670	79.24	50	52	50	2
20	6	6	69,600	86.41	58	60	60	2
21	4	4	94,900	77.85	64	66	66	2
22	1	18	16,000	79.88	68	70	68	2
23	1	9	11,840	77.85	86	88	88	2
24	2	10	12,160	82.62	95	97	97	2
25	2	10	12,160	82.62	105	107	105	2
26	5	4	260,601	84.44	81	81	81	0
27	6	6	70,760	86.41	85	85	85	0
28	5	3	94,125	77.85	91	91	91	0
29	2	9	17,360	79.88	94	94	94	0
30	2	5	12,400	77.85	103	103	103	0
31	2	9	11,780	82.62	108	108	108	0
32	1	5	13,950	83.64	117	117	117	0

Table III.
The solution for a sample case study X

resources, the multiple objectives of time, cost and quality need to be satisfied. The activity duration is affected by the selection of construction method, materials and crew sizes. By taking different combinations of the above, many schedules are possible with different time, cost and quality values. This paper proposes a framework for identifying the best schedule making acceptable compromises among these conflicting objectives. In the proposed methodology, a multi-mode RCPSP is formulated and solved using multi-objective optimization. The methodology is validated using real construction projects.

The conclusions from the application of the methodology to real cases are the following:

- It is feasible to adopt multi-objective optimization to practical construction projects using time, cost and quality as the objectives. Data required for optimization can be compiled from past completed projects for planning and scheduling of similar kinds of projects.
- A large number of activity execution plans are possible by taking different combinations of construction methods, materials and crew sizes. Robust optimization algorithms are needed to identify the best solutions among them.
- Pareto surfaces show trends that are intuitive. Cost can be reduced by increasing the duration and quality can be improved only by increasing the cost. Pareto optimization helps to quantify these relationships.

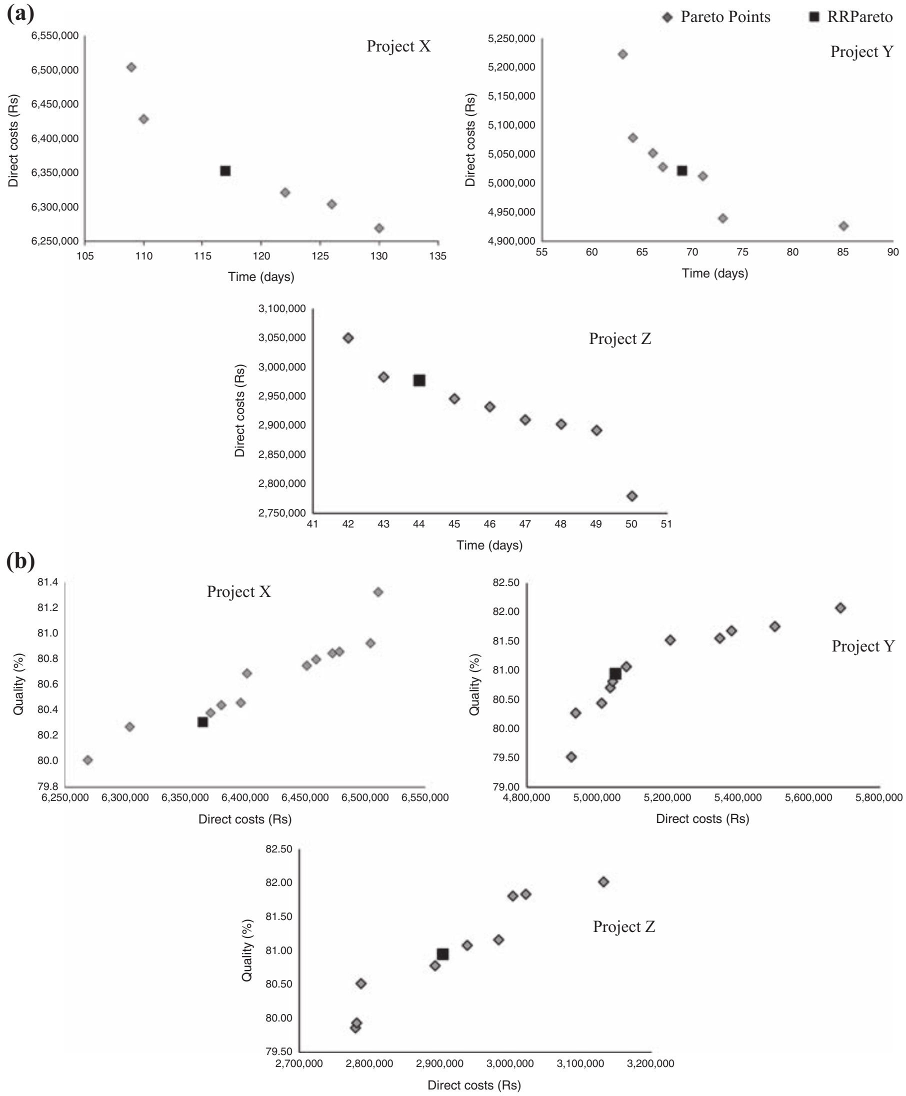
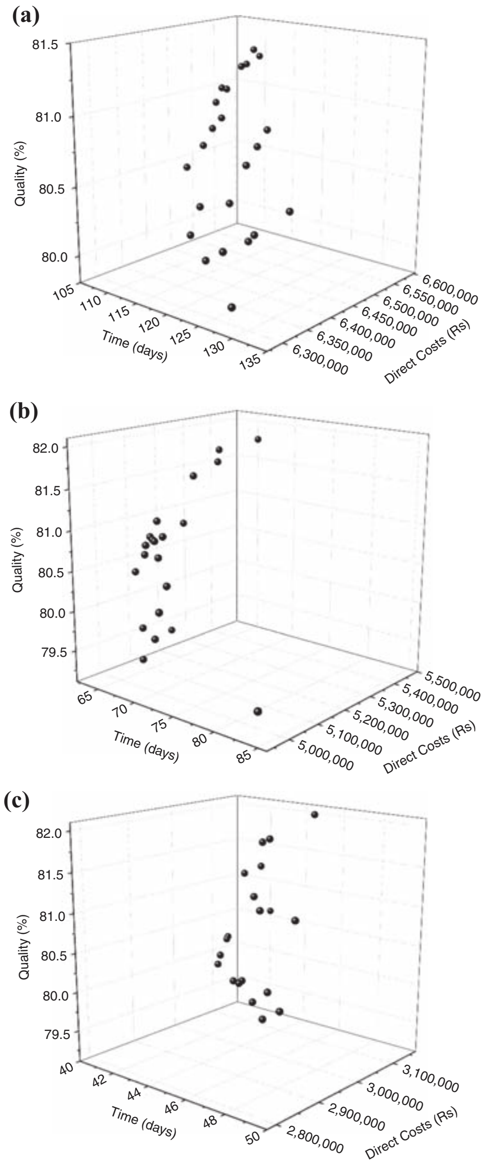


Figure 2.
Pareto front for the sample case study projects

Notes: (a) Relationship between time–cost of sample case study projects; (b) relationship between cost–quality of sample case study projects

The proposed approach supports construction planners to make managerial decisions during planning and scheduling as well as monitoring phase of the construction. The contributions of this paper are: a framework for predicting construction quality of activities, illustration of project performance prediction for different combination of activity execution modes which are identified from real projects, a new mathematical model for optimizing the multiple objectives of time, cost and quality and demonstration of new techniques for identifying compromise solutions in MRCPSPs. The limitations of this study are that the adoption of the CONQUAS



Notes: (a) Project X; (b) Project Y; (c) Project Z

Figure 3.
3D plot for the sample case study projects

Table IV.
Optimized solutions for the multi-mode resource-constrained project scheduling

	Project X	Project Y	Project Z
Best compromise (*t*, *c*, *q*)	122, 6,401,938, 80.69	66, 5,090,036, 80.81	48, 2,937,754, 81.08
Minimum duration (*d*)	109	63	42
Minimum direct cost (₹)	6,269,619	4,926,532	2,779,462
Maximum quality (%)	81.33	82.08	82.02

framework is checked only for the structural and architectural components of residential building construction projects in India. The identified activity execution modes are not an exhaustive list regarding construction methods, materials and crew sizes. Future research may incorporate life-cycle cost in the optimization model, which involves asset management considerations.

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