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A Multi Skill-based Project Scheduling and Materials Ordering Problem under Constrained Resources

Md. Limonur Rahman Lingkon
Department of Industrial & Production Engineering
Rajshahi University of Engineering & Technology
Rajshahi-6204, Bangladesh
limonur.rahman@ipe.ruet.ac.bd

Md. Asadujjaman
Department of Industrial & Production Engineering
Rajshahi University of Engineering & Technology
Rajshahi-6204, Bangladesh
asadujjaman@ipe.ruet.ac.bd

Abstract

Efficient project execution increasingly depends on the synchronized management of human skills and material resources, particularly in complex and dynamic industrial environments. In this paper, a multi-skilled resource-constrained project scheduling problem (MSRCPSP) is presented, which integrates activity scheduling, workforce utilization, equipment logistics, and material ordering within a construction project. A mixed-integer programming (MIP) model is developed for optimizing project completion time, considering both renewable and non-renewable resources. This paper demonstrates the interaction among the allocation of a multi-skilled workforce, equipment limitations, materials ordering and scheduling of projects activities. The optimal project schedule is determined, and a sensitivity analysis is conducted to assess the impact of variations in key parameters on the project completion time. The findings serve to illustrate the trade-offs among resource allocation, cost optimization, and schedule adherence. The work contributes to the growing body of research on integrated project scheduling and material ordering by combining various types of resources, cost elements, and financial considerations into a single optimization model.

Keywords
Multi-skilled resource-constrained project scheduling, Material ordering, Mixed-integer programming, Discounted cash flows, Construction project scheduling.

1. Introduction

Project-based industries, such as construction and infrastructure, must deliver complex projects under tight time and cost constraints while relying on limited labor, equipment, and materials. The resource-constrained project scheduling problem (RCPSP) has therefore become a central model in project management research, capturing how precedence-related activities compete for scarce renewable resources (Artigues et al., 2026). Classical RCPSP model, and many of their recent variants, still treat material availability and financial flows as exogenous. Even though, empirical and review papers show that integrating project scheduling with material ordering can substantially improve total project cost and resource utilization (Parchami Afra et al., 2022). A few studies considered the integration of project scheduling with materials ordering such as Asadujjaman et al. (2021) and Asadujjaman et al. (2025), however these studies neglect the skills of the workers in executing project activities.

Real life projects typically rely on multi-skilled workers and shared resources such as construction equipment; rather than homogeneous resource pools. Recent systematic reviews of the multi-skilled RCPSP emphasize the benefits of explicitly modelling skill profiles, flexible assignments, and complex resource interactions, however also note that most studies ignore procurement and inventory decisions (Bahroun et al. 2024). Similarly, research related to project scheduling with material planning rarely incorporates detailed logistics for multi-skilled workforces and equipment in a single framework. As a result, a gap remains between cost-oriented, inventory-aware models and rich resource-scheduling formulations that accurately reflect the actual scenario of construction projects.

This paper addresses that gap by proposing a deterministic mixed-integer programming (MIP) model for the multi-skilled resource-constrained project scheduling problem (MSRCPSP), which jointly determines activity start times, multi-skilled workforce assignments, equipment allocation, and material ordering for a construction project. The project network comprises sixteen activities, including two dummy activities, supported by both renewable and non-renewable resources. The model captures equipment transfer times, material lead times, carrier with limited capacity, and on-site warehouse inventory for materials. All major cost components, such as ordering, inventory holding, workers' salaries, equipment operation, and project tardiness penalties, are time-dependent and evaluated within a discounted cash-flow objective. The proposed model is solved using exact method with a mixed-integer programming solver, and optimal solutions are thereby obtained for the study, providing a rigorous benchmark for integrated scheduling and material-ordering decisions. Thus, the contribution of this study is twofold. Firstly, this study develops a multi-skilled resource-constrained project scheduling problem (MSRCPSP) model, which integrates the allocation of multi-skilled workers, equipment logistics, and material ordering within the context of project scheduling. Secondly, an exact method is used to determine the project's minimum makespan of the proposed MSRCPSP. By optimizing activity start times, workforce assignments, equipment allocation, and material procurement, the model aims to minimize the total completion time while considering various project constraints. This approach is designed to provide an optimal solution for the efficient management of resources and materials, ensuring that the project is completed within the shortest possible time frame without exceeding the available resources or budget.

The paper is organized as follows: Section 2 provides a comprehensive literature review, while Section 3 outlines the methodology and model formulation. Section 4 details the data collection. The results analysis, accompanied by a discussion, are presented in Section 5. Finally, Section 6 concludes the paper and highlights potential areas for future research.

2. Literature Review

The RCPSP is one of the most significant and thoroughly investigated combinatorial optimization problems in the domain of operations research and project management, serving as a foundational model for allocating limited resources to project activities over time. Hartmann & Briskorn (2010) provided a detailed survey on RCPSP variants and showed how the basic model has been extended with multi-mode activities, alternative objectives, and different resource structures. More recent studies confirm that RCPSP is still a very active research area, however they note that many models treat material availability and financial aspects as separate from the core decisions related to scheduling (Hartmann & Briskorn, 2022).

A second stream of research brings cash-flow and time-value-of-money considerations into project scheduling. Leyman & Vanhoucke (2017) studied the RCPSP with discounted cash flows and demonstrated that adjusting activity start times can improve not only the net present value (NPV) but also the project completion time. In follow-up research, they extended this idea to capital- and resource-constrained settings, again using discounted cash flows. In this consequence, Zhao et al. (2016) considered an uncertain RCPSP with discounted cash flows and demonstrated how financial criteria and schedule interacts with risk. These studies clearly demonstrate that financial analysis can be integrated into the scheduling model, but they do not explicitly address material ordering or the detailed structure of the resources utilized in the project.

In parallel, other authors have integrated project scheduling with material ordering and procurement. Early research has already demonstrated that addressing activity durations and ordering decisions simultaneously can reduce total costs by improving coordination between deliveries, stock levels, and project progress. More recently, Asadujjaman et al. (2021) introduced the resource-constrained project scheduling and material ordering problem with discounted cash flows. Their model jointly determines activity start times, order quantities, supplier selection, and inventory levels under resource constraints and lead times, using a discounted cash flow approach. Later, they extended their research to supply chain-integrated resource-constrained multi-project scheduling (Asadujjaman et al., 2024). A recent review by Banihashemi and Khalilzadeh (2022) highlighted this model as the first full integration of RCPSP, material ordering, and discounted cash flows, and calls for further work that adds more realistic resource structures. However, in these integrated models, workers of the projects are usually represented as a single undifferentiated capacity. The workforce is not multi-skilled, and equipment logistics, such as transfer times and carrier capacity, are often simplified or ignored (Edalatpour et al., 2025).

Beyond single-project project scheduling models, several authors have explored richer forms of integration between project scheduling, material ordering, and supply management. Fu (2014) developed one of the earliest integrated project scheduling and material planning models, where activity durations and order quantities are optimized jointly to balance schedule and inventory costs. More recently, few have provided systematic reviews of integrated project scheduling and material ordering problems, documenting a wide range of formulations that include storage constraints, supplier selection, and different cost structures, and emphasizing that integrated planning can significantly improve total project cost performance (Mozhdehi et al., 2024; Parchami Afra et al., 2022). Hartmann & Briskorn, (2022) further extended this line of work by jointly optimising activity scheduling, storage space allocation, and material ordering under limited warehouse capacity, while Liu et al. (2023) combined a multimodal RCPSP with a quantity-discount material ordering problem in a single cost-minimization model. In a multi-project and sustainability-oriented context, Pérez Armas et al. (2024) integrated multi-mode resource-constrained multi-project scheduling with supply management and environmental objectives under uncertainty.

At the same time, a fast-growing literature has emerged on the multi-skilled RCPSP (MS-RCPSP) (Hosseinian, 2026). Zhang et al. (2025) showed that in many real projects, workers and sometimes machines can perform several types of tasks, and this flexibility must be managed carefully. Bahroun et al. (2024) provided a systematic review of diversity in skills and tasks related papers and showed that modelling skills and flexible assignments can improve resource utilization and project robustness. Yet, this body of research almost always assumes that materials are available when needed and that procurement, inventory, and cash flows are handled outside the scheduling model.

Upon examining these three lines of research, RCPSP with discounted cash flows, integrated scheduling and material ordering, and multi-skilled resource scheduling, it can be observed that most papers address at most two of them simultaneously. To the best of our knowledge, the specific combination of multi-skilled project scheduling, detailed equipment logistics, integrated material ordering, and discounted cash-flow optimization has not been reported before.

3. Methods

The overall methodological framework is presented in Figure 1. The steps in the flowchart are carried out in a fixed order to build and solve the project planning model.

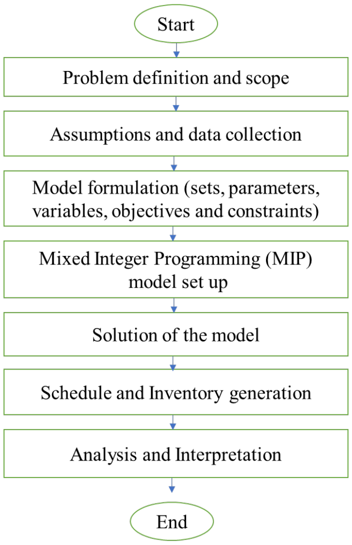


Figure 1. Overall framework of this study

Firstly, the problem is defined. The project to be studied is chosen, and all activities from start to finish are listed. The required resources (workers, equipment, and materials) are also identified. The main objective is also stated, which is to minimize the total completion time of the project maintain all the constraints.

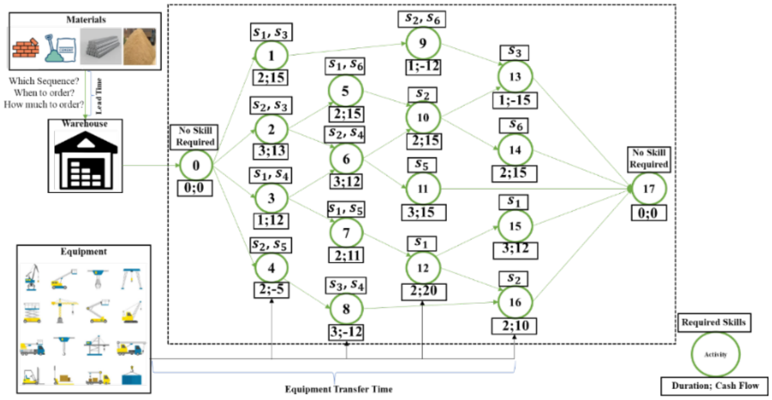
Secondly, assumptions are made and data are collected. Then, all required entities are gathered: activity durations, precedence relations, skill requirements, resource capacities, lead times, costs, and the discount rate.

After that, the model is set up. Sets for activities, time periods, workers, equipment, and materials are defined. Parameters that contain the input data are specified. Decision variables are introduced to represent the variables that must be decided upon. Then, a mixed-integer programming (MIP) model is formulated. A bi-objective function is developed to measure the total discounted cost, including ordering, holding, salaries, equipment use, and penalty costs. Constraints are added to ensure that precedence relations, capacity limits, skill requirements, equipment transfers, and material balances are all satisfied. Next, the model is implemented and solved using the exact method in an optimization solver. The solver is allowed to search the space of feasible solutions until an optimal one is found, given the set of constraints and data. Finally, schedules and inventory graphs are generated from the optimal solution, and the results are analyzed. The timing of activities, the use of workers and equipment, the order times, the inventory profiles, and the total cost are all evaluated to provide useful insights for the project.

3.1 Model Formulation

This section represents the model formulation. Figure 2 presents the model architecture for the considered projects. In this figure, nodes 1–16 represent the real activities, while nodes 0 and 17 are the dummy start and finish nodes, respectively. Arrows between the nodes show precedence relations. An arrow from one activity to another means that the first activity must be finished before the next one can start. On the left side, materials (such as bricks, cement, and rods) are depicted as being sourced from fixed suppliers and delivered to a warehouse. From the warehouse, materials are then available for the activities that need them.

At the bottom left, several icons represent different types of equipment (e.g., cranes, mixers, trucks), which are shared among the activities during the project. Then, in the bottom part of the figure, two tables present the activity-worker-skill assignment and their relationships. Together, these two tables explain how the multi-skilled workforce is defined and how specific workers are assigned to each activity in the project network.



Skill vs. Workforce		Skills Required for Work					
		s_1	s_2	s_3	s_4	s_5	s_6
Workforce Required	w_1	✓	×	✓	×	✓	×
	w_2	✓	✓	×	✓	×	×
	w_3	×	✓	✓	×	×	✓
	w_4	✓	×	✓	×	✓	✓
	w_5	✓	✓	×	✓	×	✓
	w_6	×	✓	✓	×	×	✓
	w_7	×	✓	✓	✓	×	✓
	w_8	✓	×	✓	✓	✓	×
	w_9	✓	✓	×	×	×	✓
	w_{10}	×	✓	×	✓	✓	×
	w_{11}	✓	×	✓	×	×	✓
	w_{12}	✓	✓	×	×	✓	×
	w_{13}	✓	×	✓	✓	×	✓

Activity Involvement	Worker Involvement	
A_1	w_1	w_4
A_2	w_3	w_7
A_3	w_5	w_8
A_4	w_{10}	w_{12}
A_5	w_5	w_9
A_6	w_7	w_{10}
A_7	w_8	w_{12}
A_8	w_{13}	w_8
A_9	w_3	w_9
A_{10}	w_2	×
A_{11}	w_{10}	×
A_{12}	w_{13}	×
A_{13}	w_1	×
A_{14}	w_7	×
A_{15}	w_{11}	×
A_{16}	w_6	×

Figure 2. Model Architecture

The model depicts one construction project having 16 real activities and two dummy nodes (0 and 17). Activities are non-preemptive and single-mode, meaning that once an activity is initiated, it runs to completion without interruption and may require many workers and equipment with specific skills during any given period. There are two types of resources considered: renewable resources (encompassing multi-skilled workers and equipment) and non-renewable resources (encompassing materials). A worker can be allocated at most one activity per period, and equipment can be assigned to at most one activity per period; no transfer time is assumed (workers are already present on-site). All workers are paid the same daily salary. The equipment and materials are also sourced from one fixed supplier. Only once equipment is shipped to the project, transfer time and limited carrier capacity are considered, and materials are affected by lead time. The first order is made at time zero, and warehouse capacity is assumed to be adequate; hence, no relation with overflow or transport stock is considered. Costs depend on time, and include ordering costs, inventory holding costs, worker salaries, equipment operating costs (both during busy and idle times), and penalty costs due to late project completion. Cash outflow occurs upon the initiation of activities, and cash inflows are realized upon completion of activities. The set, indices, parameters, and decision variables for this paper are presented in Table 1.

Table 1. Set, indices, parameters, and decision variables

Set and Indices	
ψ	Set of the activities ($j = 0,1,2,\dots,J,J+1$); 0 & ($J+1$) is the dummy activities.
χ	Discrete time periods; ($t = 1,2,\dots,T$)
S	Set of skills required for the activities; ($s = 1,2,\dots,S$)
W	Set of workers; ($w = 1,2,\dots,W$)
E	Set of required equipment; ($e = 1,2,\dots,E$)
M	Set of required materials for the project; ($m = 1,2,\dots,M$)
O	Set of orders; ($o = 1,2,\dots,O$)
$Pred$	Precedence arcs (j,j')
Parameters	
J	Number of activities (dummy activities are excluded)
W	Number of available workers
E	Number of available equipment
T	Number of time periods in the planning horizon
M	Number of type of materials
ξ_j	Duration of activity *j* of the project
$\chi_{j,s}$	Units of multi skilled worker required to perform skill *s* for activity *j*
$OJ_{w,s}$	$\begin{cases} 1, & worker\ w\ is\ competent\ of\ skill\ s \\ 0, & elsewhere \end{cases}$
A_s	Availability of workers with skill *s* in each time period
$NE_{j,t}$	Number of required equipment by the activity *j* at time *t*
$HC_{m,t}$	Holding cost of the materials type *m* at the time *t*
SC_m	Storage capacity for the material type *m*
$\zeta_{w,t}$	Salary of the worker *w* in time *t*
$OPC_{q,t}$	Operating cost of the equipment *q* in time *t*
PC_t	Penalty cost incurred for the time *t* on the project, if the due date is exceeded
OC_o	Ordering cost per order *o*
$QM_{j,m,t}$	Quantity of material type *m* needed by the quantity *j* in the time *t*
$UP_{m,t}$	Unit price of material *m* at time *t*
OCO_j	Other cash outflow for exceeding activity *j*
ELT_m	Expected lead time material type *m*
ETT_e	Expected transfer time for the equipment *e*
INE	Initial on-site unit of the equipment *e*
DUP	Due date for the project (deadline period)
CI_j	Cash inflow received upon the completion of the activity *j*
α	Discount rate (0.05)

Decision Variable	
$I_{m,t}$	Inventory at time *t* for the quantity of material type *m* available (≥ 0)
$QT_{m,t}$	Quantity of material type *m* (≥ 0) ordered in the time *t*
$V_{j,t}$	$\begin{cases} 1, & Activity\ j\ commences\ at\ time\ t \\ 0, & elsewhere \end{cases}$
$\gamma_{j,t}$	$\begin{cases} 1, & Activity\ j\ progress\ at\ time\ t \\ 0, & elsewhere \end{cases}$
STT_j	Starting time of the activity *j*
FTT_j	Finishing time of the activity *j*
$\vartheta_{j,w,s,t}$	$\begin{cases} 1, & worker\ w\ perform\ skill\ s\ for\ activity\ j\ at\ time\ t \\ 0, & elsewhere \end{cases}$
$\tau_{j,e,t}$	$\begin{cases} 1, & equipment\ e\ operating\ on\ activity\ j\ at\ time\ t \\ 0, & elsewhere \end{cases}$
$U_{j,e,t}$	$\begin{cases} 1, & equipment\ e\ used\ by\ activity\ j\ at\ time\ t \\ 0, & elsewhere \end{cases}$
OT_o	Order time for order *o*

The formulation for the MSRCPSP that aims to minimize the project's total completion time is presented in Eq. (1).

$$\text{Min } Z\ (Total\ completion\ time) = max_j(FTT_j) \qquad (1)$$

Eq. (2) indicates that the quantity of material needed as the progress of the activities will be less than the available materials in the inventory.

$$\sum_{j=1}^{J} QM_{j,m,t} \times \gamma_{j,t} \leq I_{m,t} \qquad \forall m, \forall t \qquad (2)$$

$$FTT_j \leq FTT_{j+1} - \xi_j \qquad \forall j \qquad (3)$$

Eq. (3) indicates the precedence relationship among the activities.

$$FTT_j = STT_j + \xi_j \qquad \forall j \qquad (4)$$

Eq. (4) indicates the precedence relationship among the activities also.

$$STT_j = \begin{cases} \max_{j' \in \Lambda j}(FTT_{j'}) & if\ \max_{j' \in \Lambda j}(FTT_{j'}) \geq ETT_e \\ \max\{\max_{j' \in \Lambda j}(FTT_{j'}), ETT_e\}, & if\ \max_{j' \in \Lambda j}(FTT_{j'}) \leq ETT_e \end{cases} \qquad \forall j, \forall (j,j') \in Pred \qquad (5)$$

Eq. (5) indicates that starting time of each activity depends on two factors: (i) Finish time of the immediate predecessors; (ii) Arrival of the required equipment.

$$\sum_{t=1}^{T} \sum_{j=1}^{J} U_{j,e,t} = 1 \qquad \forall e \qquad (6)$$

Eq. (6) ensures that each equipment will be transported to the project once.

$$\sum_{t=1}^{T} \sum_{s=1}^{S} \vartheta_{j,w,s,t} \leq 1 \qquad \forall e \qquad (7)$$

Eq. (7) ensures that each worker merely able to execute one activity in each time period.

$$\sum_{j=1}^{J} \tau_{j,e,t} \leq 1 \qquad \forall e, \forall t \qquad (8)$$

Eq. (8) ensures that each equipment merely able to operate one activity in each time period.

$$\vartheta_{j,w,s,t} \leq \gamma_{j,t} \qquad \forall w, \forall t, \forall j, \forall s \qquad (9)$$

Eq. (9) indicates the progress of the work based on the worker involvement of specific skills for an activity in a time period.

$$\tau_{j,e,t} \leq \gamma_{j,t} \qquad \forall j, \forall t, \forall e \qquad (10)$$

Eq. (10) indicates the progress of the work based on the equipment involvement for an activity in a time period.

$$\vartheta_{j,w,s,t} \leq OJ_{w,s} \qquad \forall w, \forall t, \forall j, \forall s \qquad (11)$$

Eq. (11) indicates that the workers can only can be assigned to their possessed skill which is less than or equal to the worker competent at performing that skill.

$$QT_{m,t} = \sum_{j=1}^{J} \gamma_{j,(t+ELT_m)} \times QM_{j,m,(t+ELT_m)} \leq 1 \qquad \forall m, \forall t \qquad (12)$$

Eq. (12) ensures that specific required quantity of materials ordered in each time period.

$$I_{m,t} = I_{m,(t-1)} - \sum_{j=1}^{J} (\gamma_{j,t} \times QM_{j,m,t}) + QT_{m,t-ELT_m} \qquad \forall m, \forall t \qquad (13)$$

Eq. (13) ensures the inventory level of each required materials ordered in each time period.

$$\sum_{j=1}^{J} (\chi_{j,s} \times \gamma_{j,t}) \leq A_s \qquad \forall s, \forall t \qquad (14)$$

Eq. (14) satisfies the limited access to the workers (multi skilled) with their skill. It ensures the availability of the workers.

$$INE - \sum_{j=1}^{J} \sum_{e=1}^{E} U_{j,e,t} \leq \sum_{j=1}^{J} NE_{j,t} \qquad \forall t \qquad (15)$$

Eq. (15) indicates that number of available equipment will be less than or equal to the number of required equipment.

$$\sum_{t=1}^{T} V_{j,t} = 1 \qquad \forall j \qquad (16)$$

Eq. (16) indicates that project activity only be commenced in one of the time periods.

$$I_{m,t} \leq SC_m \qquad \forall m, \forall t \qquad (17)$$

Eq. (17) indicates that capacity of storage of materials always larger than the level of inventory.

$$\tau_{j,e,t} \leq U_{j,e,t} \qquad \forall m, \forall e, \forall t \qquad (18)$$

Eq. (18) indicates that equipment can be assigned to an activity if it has been already received and mounted on the project.

$$ETT_e, ELT_m, I_{m,t}, QT_{m,t}, FTT_j, STT_j \geq 0 \qquad \forall m, \forall j, \forall t \qquad (19)$$

Eq. (19) indicates the non-negativity constraints.

$$V_{j,t}, \gamma_{j,t}, U_{j,e,t}, \tau_{j,e,t}, \vartheta_{j,w,s,t} \in \{0,1\} \qquad \forall j, \forall s, \forall w, \forall e, \forall t \qquad (20)$$

Eq. (20) indicates the range of the value of the variables.

$$FTT_j \ integer \qquad \forall j \qquad (21)$$

Eq. (21) indicates that the finish time of the activities belonging to the project must be an integer.

4. Data Collection

Data was collected from a construction project. The activities of the project are presented in Table 2, and Table 3 presents the details of the skills required for the activities involved in the project. Data related to activity duration, skills required for the activity, and precedence relationships are presented in Figure 2. Rest of the data is confidential.

Table 2. Activities of the projects

Activity No.	Activity Details
A_1	Site clearing/access road
A_2	Ground marking and surveying
A_3	Temporary facilities (site office, storage)
A_4	Safety setup and perimeter fencing
A_5	Foundation works (footings/pads)
A_6	Underground plumbing and electrical conduits
A_7	Column and beam reinforcement (ground floor)
A_8	Ground floor slab/base slab
A_9	Superstructure frame (columns/beams, upper levels)
A_{10}	Staircase/core works
A_{11}	Roof slab / upper slab
A_{12}	Internal and external brick/block walls
A_{13}	Doors/windows and external finishes
A_{14}	Internal plastering and ceilings
A_{15}	MEP fixtures (lights, switches, sanitaryware)
A_{16}	Painting, flooring, and final detailing

Table 3. Skills required for the activities

Activity No.	Activity Details
S_1	Site setup, earthworks, material handling
S_2	Structural/concrete/reinforcement
S_3	Masonry and block/brick work
S_4	MEP rough-in (plumbing and electrical)
S_5	Finishes (plaster, paint, doors/windows, painting, flooring, fittings)
S_6	Supervision, safety, and quality control

5. Results and Discussion

This section first presents the numerical and graphical results analysis and finally end with the sensitivity analysis.

5.1 Numerical Results

Table 4 shows the result of the numerical example for this study. The project has a duration of 0, 2, 3, 1, 1, 2, 3, 2, 3, 1, 2, 3, 2, 1, 2, 3, 2, and 0 for activity 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 respectively. The renewable resource-1 (workers) for these activities is 0, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1, 1, 1, and 0, respectively. The renewable resource-2 (equipment) for these activities is 0, 1, 2, 1, 1, 1, 2, 1, 1, 1, 2, 1, 1, 1, 1, 2, 1, and 0, respectively. The project manager is planning to execute the project with a sequence of 0-1-2-3-4-7-5-6-8-9-11-10-12-14-13-16-15-17, where the start time of the activities is 0-3-3-3-3-5-6-6-7-8-9-9-10-11-11-12-12-15, with the finish time of 0-5-6-4-4-7-8-9-10-9-12-11-12-13-12-14-15-15. As the maximum lead time is 3, the resource order time for the activities is 0-0-0-0-1-2-3-3-4-5-6-6-7-8-8-9-9-9-12.

Table 4. Optimal sequence with order time

Seq.	0	1	2	3	4	7	5	6	8	9	11	10	12	14	13	16	15	17
STT	0	3	3	3	3	5	6	6	7	8	9	9	10	11	11	12	12	15
FTT	0	5	6	4	4	7	8	9	10	9	12	11	12	13	12	14	15	15
OT	0	0	0	0	1	2	3	3	4	5	6	6	7	8	8	9	9	12

5.2 Graphical Results

Figure 3 shows the activity schedule against the renewable resource-1 i.e. the workers. Duration of the activity is presented on the horizontal axis, and each row depicts usage of a worker. Light-grey bars labelled A_1 –A_{16} mark the intervals of time that the worker participates in a particular task, and the red bars marked with the label of Idle indicate the intervals when the worker is not working but is nevertheless on location. The blue bracket to the left indicates the accumulated time of the lead and transfer prior to the commencement of on-site work, and the orange dashed line to the right indicates the project deadline.

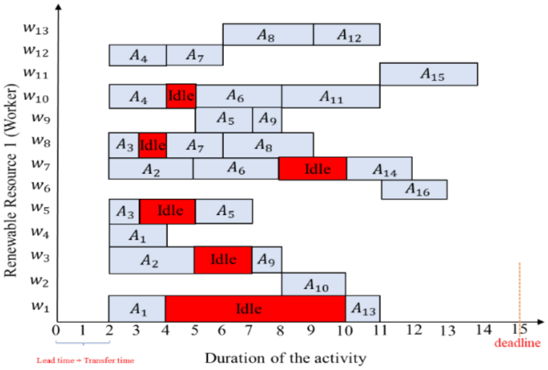


Figure 3. Schedule of the activities with respect to renewable resource-1

The schedule of activities related to renewable resource 2, equipment, is illustrated in Figure 4.

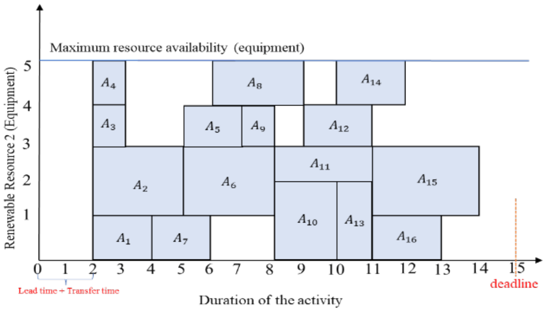


Figure 4. Schedule of the activities with respect to renewable resource-2

The labels on the blocks representing activities indicate the time period during which one or more units of equipment are required to execute the activity. The maximum equipment viability in the figure is 5 units. The precedence relations and equipment availability are indicated in the arrangement of blocks; thus, the overlaps indicate the time when multiple activities use equipment concurrently.

Figure 5 presents activities with respect to non-renewable resources, which are the materials required during the project, where maximum material availability is 100 units.

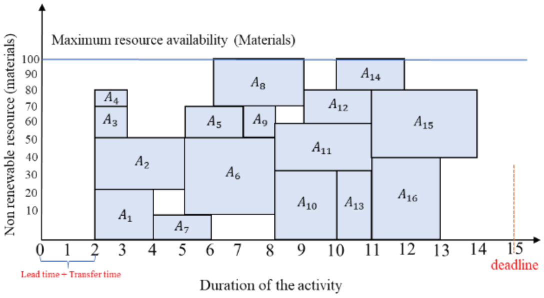


Figure 5. Schedule of the activities with respect to non-renewable resources

Figure 6 represents the level of inventory with respect to the activities. This figure shows the maximum resource (material) line. Maximum resource availability is 100 units with the overall completion time of the project is 15 which meets the deadline of 15.

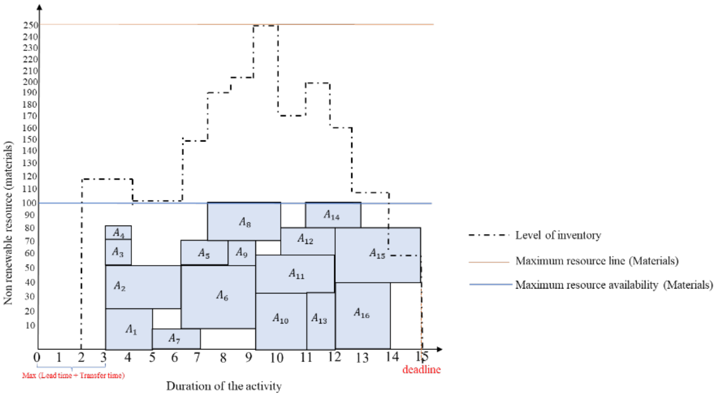


Figure 6. Inventory level with activities

Figure 7 shows the warehouse inventory level at each time period. The inventory is 0 units at 1, 120 units at 2 and 3, 100 units at 4 and 5, 150 units at 6, 190 units at 7, 220 units at 8, and reaches its maximum of 250 units at 9. It then decreases to 180 at time 10, rises slightly to 200 units at 11, and continues to fall to 160, 120 and 70 units at 12, 13 and 14, respectively, before returning to 0 units at time 15.

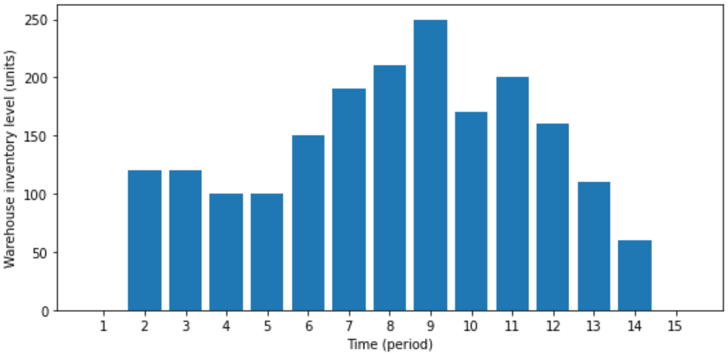


Figure 7. Level of inventory for resources (materials) over time

5.3 Sensitivity Analysis

In this section, four main parameters of the model are changed: equipment operating cost, ordering cost, penalty cost for exceeding the due date, and warehouse capacity. Figure 8 represents the sensitivity analysis. For each of these, the original value is considered as a base. Then the value is reduced and increased by 5%, 10%, 15%, and 20%, one parameter at a time, while the others are kept fixed. For every change, the model is solved again. The results, shown in Figure 8, indicate how these changes affect the project completion time.

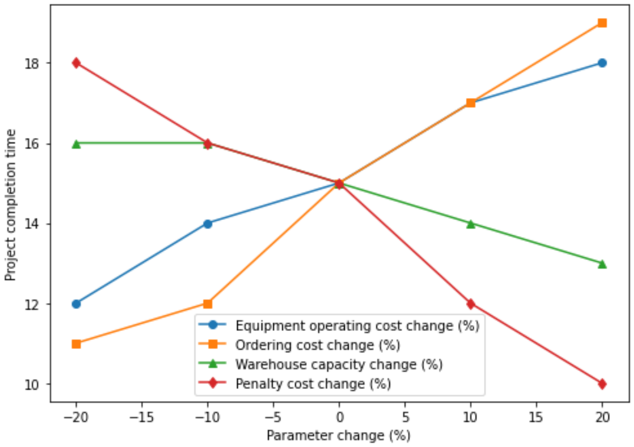


Figure 8. Sensitivity Analysis

With no changes, all parameters retain their initial completion time, and the project concludes after 15 periods. A decrease in equipment operating costs and ordering costs will result in slower project completion, whereas an increase in these costs will also slow the project's completion, as the project model will allocate more resources to equipment and ordering, thereby increasing the project's completion time. Warehouse capacity works in the opposite way: when the capacity is low, the project completion time is longer, and a high capacity results in a shorter time because more material can be stored and used without interruption. Variations in the cost of penalties also affect the schedule: with lower penalties, it will take longer to complete the project, and with higher penalty costs, it will take less time.

6. Conclusion and Future Scope

The study developed a MIP model to solve the MSRCPSP, which integrates activity scheduling with multi-skilled labor, equipment, and material ordering. The main objective was to simulate the effect of these interdependent factors on the time and cost of project completion, providing a more realistic scheduling tool for project managers. The model addresses key issues in real-life building projects by integrating renewable and non-renewable resources. The model successfully determined the optimal project schedule and resource plan simultaneously. Sensitivity analysis highlighted critical trade-offs between resource allocation, cost, and schedule adherence., as well as costs and penalties that vary over time. The findings revealed that the project is relatively resilient to such changes; however, certain parameters, such as ordering cost and penalty cost, have a more significant impact on the project timeline. However, a key limitation of this study is that the model assumes a fully deterministic environment, such as durations, lead times, and resource availability. For future work, this model can be extended to incorporate uncertainty in key parameters such as activity durations, material lead times, equipment transfer time, and resource availability. The integration of advanced heuristics or metaheuristics could also help solve larger, real-world instances more efficiently.

References

Artigues, C., Hartmann, S., and Vanhoucke, M., Fifty years of research on resource-constrained project scheduling explored from different perspectives, *European Journal of Operational Research*, vol. 328, no. 2, pp. 367-389, 2025.

Asadujjaman, M., Rahman, H. F., Chakrabortty, R. K., and Ryan, M. J., Resource constrained project scheduling and material ordering problem with discounted cash flows, *Computers and Industrial Engineering*, vol. 158, no. 2, pp. 107427, 2021.

Asadujjaman, Md., Rahman, H.F., Chakrabortty, R.K. and Ryan, M.J., Supply chain integrated resource-constrained multi-project scheduling problem, *Computers & Industrial Engineering*, vol. 194, pp.110380, 2024.

Bahroun, Z., As'Ad, R., Tanash, M., and Athamneh, R., The Multi-Skilled Resource-Constrained Project Scheduling Problem: A Systematic Review and an Exploration of Future Landscapes, *Management Systems in Production Engineering*, vol. 32, no. 1, pp. 108-132, 2024.

Banihashemi, S. A., and Khalilzadeh, M., A Robust Bi-objective Optimization Model for Resource Levelling Project Scheduling Problem with Discounted Cash Flows, *KSCE Journal of Civil Engineering*, vol. 26, no. 1, pp. 1-16, 2022.

Edalatpour, M. A., Mirzapour Al-e-Hashem, S. M. J., and Ghasemi, S., Harmonizing project management and supply chain for sustainable construction: A comprehensive mathematical model and case study. *Sustainable Futures*, vol. 10, pp. 100805, 2024.

Fu, F., Integrated scheduling and batch ordering for construction project. *Applied Mathematical Modelling*, vol. 38, no. 2, pp. 784-797, 2014.

Hartmann, S., and Briskorn, D., A survey of variants and extensions of the resource-constrained project scheduling problem, *European Journal of Operational Research* vol. 297, no. 1, pp. 1-14 2014.

Hartmann, S., and Briskorn, D., An updated survey of variants and extensions of the resource-constrained project scheduling problem, *European Journal of Operational Research,* vol. 297, no. 1, pp. 1–14, 2022.

Hosseinian, A. H., Modeling of the multi-skilled project scheduling and material ordering problems for the offshore construction projects considering uncertain lead times and resource transfer times. *Computers & Industrial Engineering*, vol. 211, pp. 111646, 2025.

Leyman, P., & Vanhoucke, M., Capital- and resource-constrained project scheduling with net present value optimization. *European Journal of Operational Research*, vol. 256, no. 3, pp. 757–776, 2017.

Liu, Y., Huang, L., Liu, X., Ji, G., Cheng, X., and Onstein, E., A late-mover genetic algorithm for resource-constrained project-scheduling problems, *Information Sciences*, vol. 642, pp. 119164, 2023.

Mozhdehi, S., Baradaran, V., and Hosseinian, A. H., Multi-skilled resource-constrained multi-project scheduling problem with dexterity improvement of workforce, *Automation in Construction*, vo. *162, pp. 105360, 2024*.

Parchami Afra, A., Kheirkhah, A., and Ahadi, H., Systematic literature review of integrated project scheduling and material ordering problem: Formulations and solution methods, *Computers and Industrial Engineering*, vol. 173, pp. 108711, 2022.

Pérez Armas, L. F., Creemers, S., and Deleplanque, S., Solving the resource constrained project scheduling problem with quantum annealing, *Scientific Reports*, vol. 14, no. 1, pp. 16784, 2024.

Zhang, Y., Cui, N., and Hu, Z., Project scheduling and material ordering with storage space constraints: priority or genetic based algorithms, *Flexible Services and Manufacturing Journal*, 2025.

Zhao, C., Ke, H., and Chen, Z., Uncertain Resource-Constrained Project Scheduling Problem with Net Present Value Criterion, *Journal of Uncertainty Analysis and Applications*, vol. 4, no. 1, 2016.

Biographies

Md. Limonur Rahman Lingkon is currently working as a Lecturer in the Department of Industrial & Production Engineering (IPE) at Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh. He completed the Bachelor of Science in Industrial & Production Engineering from RUET in 2022 by securing the **1st**

class 1st position in order of merit. He is pursuing his M.Sc. in IPE from the same university. His research interests include operations management, project management, supply chain management and circular economy.

Dr. Md. Asadujjaman is a Professor and the Head of the Department of Industrial & Production Engineering (IPE) at Rajshahi University of Engineering & Technology (RUET), Rajshahi-6204, Bangladesh. He is awarded PhD in Systems Engineering from the University of New South Wales (UNSW), Australia. He completed the Master of Science in Industrial & Production Engineering from the Bangladesh University of Engineering & Technology (BUET) in 2015. He completed the Bachelor of Science in Industrial & Production Engineering from RUET in 2012 by securing the **1st class 1st** position in order of merit. He awarded the *University Gold Medal* for his outstanding academic performance at the undergraduate level. His research covers a wide range of topics including *Supply Chain Integrated Project Scheduling, Operations Management, Operations Research, Financial Engineering, Ergonomics and Human Factors Engineering, Forensic Anthropometry.* He is the author/co-author over 40 refereed journal and conference papers. Dr. Md. Asadujjaman has 3 years' experience as a Casual Academic at UNSW, Australia. He is a Member of the Institution of Engineers Bangladesh (IEB), and the Decision Support and Analytics Research Group at UNSW Canberra, Australia.