A NOVEL MULTI-OBJECTIVE MULTI-MODE MULTI-SKILL MATHEMATICAL MODEL FOR TIME COST AND QUALITY TRADE-OFF IN PROJECT SCHEDULING

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Abstract - In this paper, a novel multi-objective multi-mode multi-skilled project scheduling problem (MOMMMSPSP) with a time cost quality trade-off approach is proposed. In this problem, Each Activity can be performed in different executing modes, and each mode needs different requirements; requirements in this problem are different skills, which should be done by staff. Furthermore, staff members have various skills and specialties and can perform different skills in different activities. To model this problem, an integer linear programming formulation is proposed to optimize the objectives concurrently, including (1) minimizing total project completion time, (2) minimizing the total salary of the workforce involved in performing activities, and (3) maximizing the quality of workforce on performing skills of activities. Then Lp metric technique is utilized to transform the multi-objective problem to a single objective problem and find the optimal solution; thus, the proposed Lp metric model has been solved optimally by GAMS in small-sized. Analyzing the results showed that the optimal solution obtained from an Lp metric method in small-sized is optimal and reliable. Solving the model has created reasonable and feasible solutions for small-sized problems. The proposed model is firmly NP-hard, and bringing exact solutions is time-consuming.

Keywords - L_p metric, Multi-Skilled Project Scheduling Problem, Multi-mode Resource Constraint Project-Scheduling Problem, Time Cost Quality Trade-off Problem.

I. INTRODUCTION

Over the years, project scheduling has been among the most critical areas in operational research applications. During decades from the emergence and application of project management knowledge, its concepts, dimensions, and methods are constantly expanding and improving. These changes seek to bring the proposed models closer to the real problems in today's complex world, which has led to many advances in the science of scheduling optimization.

The resource-constrained project scheduling problem (RCPSP) was first presented by [1]. RCPSP is one of the most practical problems in operations research. In recent years, significant advances have expanded its dimensions and accurate and innovative solutions. The purpose of presenting the RCPSP is to schedule the activities in the project and determine the appropriate sequence of activities so that the Precedence relations between different activities in the project are fully considered. Various limitations such as constrained resources used in the project Also are fully considered. [2] Showed that the RCPSP is an NP-Hard problem. Since the definition of this problem, much research has been done on RCPSP. The study is divided into two parts: 1) presenting various mathematical models for the RCPSP 2) providing different solution methods, including exact, heuristic, and meta-heuristic techniques. [3] proposed an integrated PSO algorithm to solve the RCPSP. They offered four different types of answer representations for the PSO algorithm, and for all of them, they used a crossover operator to improve the answers. The computational results showed that the algorithm they developed to solve the RCPSP has a high ability to provide appropriate solutions. [4] proposed a mathematical model for the RCPSP in the condition of a preemption. They offered a mathematical model for finding the optimal solution to minimize the total project time. They used a branch & price algorithm to solve the real problems presented in the literature, and their proposed algorithm was based on the column generation method. The computational results indicated the proper performance of the algorithm in solving the sample problems presented in the research literature. [5]presented a bi-objective mathematical model to make the resource transfer decisions, aiming to minimize the transfer cost and maximize solution robustness in the presence of activity duration variability because transfers of renewable resources between activities overall incur certain scheduling costs and affect the robustness of a specific schedule in an uncertain environment. They used a novel resource-oriented flow formulation that was different from previous literature. An NSGA-II and a Pareto simulated annealing (PSA) algorithm have been applied as the solution methodologies. Furthermore, the ε-constraint method was used to evaluate the effectiveness of the metaheuristics Algorithms. The results indicated that the suggested model and algorithms were applicable and beneficial to the problem in practice.

In the normal state of the RCPSP, it is assumed that each activity can only be performed in a specific mode, while in the real world, each activity can be performed in more than one mode and selectively. Thus, defining a multi-mode resource constraint project-scheduling problem(MMRCPSP) in a project is selecting a mode to perform each activity (executing mode) and determining each activity's start and finish time so that resource constraints and Precedence relations are regarded, and the project's duration is minimized.[6] developed a mixed-integer programming model for the MMRCPSP in the conditionof the preemption in activities; the objective was to minimize renewable or nonrenewable resource costs and earliness-tardiness costs by a given project deadline and due dates for activities. They proposed a genetic algorithm (GA) to solve the problem. To evaluate the quality of the proposed algorithm, 120 test problems were used. Comparative statistical results reveal that the proposed GA was efficient and effective in terms of the objective function and computational times.[7]have formulated a prefabricated building (PB) construction resource-constrained project scheduling with the multi-objective multi-mode optimization model, focusing on the uncertainty of the execution of activity's duration. They used the interval value of the execution time to express it through fuzzy theory and consider the multiple objectives, including time-based profit and cost-based profit. They also proposed a hybrid cooperative co-evolution algorithm (HCOEA) to obtain the highly robust project scheduling and reduce the uncertainty of the execution time of the overall project. They design HCOEA with multi-stage representation for the activity sequencing and the resource allocation, further improving the search efficiency. Finally, benchmarks and datasets with fuzzy processing time were adopted to test their HCOEA. Computational results showed that the HCOEA performed better than the existing state-of-the-art methods.

Time cost and quality are three critical factors in planning and controlling construction projects. The project's time, cost, and quality are determined by the project activities' time, cost, and quality. On the other hand, these criteria for each of the activities in the project network depend on its executing mode. Getting these factors in balance, which minimizes the project duration, the total project cost, and maximizes the total quality, could define the success of a construction project. Usually, using more effective execution techniques will reduce the completion time of an activity, but we will have to pay more for using more efficient resources and technologies. Generally, more inexpensive resources or technologies lead to an increase in the duration of activities and thus an increase in the entire project's duration. Utilizing resources with greater productivity and efficiency or more advanced technologies will save project time and increase the project's direct cost. Simultaneous reduction of time and cost may also lead to reduced quality of projects. Finding an optimal solution to the Time cost quality trade-offproblem (TCQTP) includes determining the optimal execution modes for all the activities that make up the project. An optimal combination of time, cost, and quality for all activities is created. As a result, the main target in TCQTP is to allocate limited resources to activities with respecting Precedence relations to achieve the predetermined goals, such as minimizing the project's completion time, minimizing the project's total cost, and maximizing the project's overall quality.[8] presented a multi-objective mathematical model for TCQTP. They assumed that the resources required for each activity mode were different, and each activity could be considered normal or preemptive. They used a meta-heuristic algorithm called the adjusted fuzzy dominance genetic algorithm to solve the problem. To evaluate the performance of the proposed multi-objective meta-heuristic algorithm, it was compared with four well-known algorithms; NSGAII, NRGA, PAES, MOIWO. The obtained results showed the effectiveness of the proposed algorithm.[9] presented a mathematical model combining multi-objective optimization problems and multi-criteria decision-making methods to model the TCQTP. They used Shannon's entropy technique to weigh the objectives of the problem. They used a multi-objective algorithm combining NSGA-II and MOGA to solve the proposed model. The results showed that the integrated algorithm has a lower solution time than the NSGA-II and MOGA algorithms.[10] Utilized fuzzy logic to model the uncertainty embedding α-cut approach to see the effect of the uncertainty on the time, cost, and quality of the project. Then multi-objective Symbiotic Organism Search (SOS) algorithm was applied to find a set of the optimal solution in different uncertainty levels and provide the project manager several possible actions to implement the project. Some numerical case studies were analyzed to find the model's effectiveness and capability to solve the TCQTP in the construction project. The results illustrated that the proposed model was powerful to find the solution for the shortest project duration with minimum incurred cost and high overall quality in the construction project. Compared to the other widely used methods and other algorithms, the proposed model was proven effective and competitive in solving the TCQTP.[11] proposed an NSGAII based TCQT optimization model for project scheduling. They assumed that each project activity had different alternatives accompanied by other times, costs, and impact on the entire project quality. The main objective was to quantitatively estimate the project's quality and determine the optimal combinations of activities alternatives while minimizing the time cost and maximizing the entire project quality. A pairwise comparison-based analytical hierarchy process (AHP) was employed to determine the relative weight of activities and quality

indicators of the project. The developed model was utilized for a case study project; Results of the case study project demonstrated the efficiency of the proposed model in simultaneous optimization of time, cost, and quality of the project.

II. MULTI-SKILL PROJECT SCHEDULING PROBLEM

The Multi-Skill Project Scheduling problem (MSPSP) was first proposed by [12]. He combined the classic RCPSP with the Multi-Purpose Machine (MPM) model to provide a model that minimizes project completion time.MSPSP is an extended model of the MMRCPSP problem. The main difference between the MSPSP problem and the RCPSP problem or the MMRCPSP problem is considered in the resources and the method of defining the requirement of each resource. In this problem, the resources are the staff members assigned to the project. The method of using these resources is determined based on the skills of each of them during the project. Therefore, in this type of problem, each human resource has a set of skills, and each activity needs a set of skills to be performed. In MSPSP, the skills of staff and the needs of each activity to different skills are defined and specified. By this definition, staff members assigned to each activity are a subset of individuals who can meet the skill needs of that activity. The large number of modes for each activity to be performed is rooted due to the ability of each member to do different skills in activities. If in MSPSP all members (resources) have only one skill, we are dealing with the same classic RCPSP model. MSPSP is the case for various disciplines, including construction, IT projects, healthcare, and process systems.[13] proposed a mathematical model that combines the RCPSP problem with the MPM problem. The purpose of presenting this model was to find the optimal schedule of activities to minimize the completion time of the whole project. They assumed that the resources used in this project were human resources with different skills. Therefore, to perform any required skill in each activity, some staff must be allocated to that activity. They proposed a new method that combines the column generation approach with the Branch & Price algorithm to solve this problem. The computational results showed that the new method used to solve the proposed model could obtain the optimal global solution of the model in small and medium sizes in a reasonable time.[14]offered a particular type of MSPSP called Multi-Objective Multi-Skilled Project Scheduling Problem (MOMSPSP), which incorporated some new objectives in the MSPSP and developed a multi-objective mixed-integer non-linear programming (MINLP) model. The model was exactly solved for small-sized instances using a CPLEX solver. Differential Evolution (DE) and Particle Swarm Optimization (PSO) based meta-heuristic algorithms were utilized to solve such an NP-hard problem for medium and large-sized instances. To evaluate the performance of the propounded algorithms, results were compared with each other and the optimal solution obtained by the CPLEX solver for small-sized instances. Finally, the designed DE algorithm was explored as the superior proposed algorithm for solving the proposed MOMSPSP in terms of some performance metrics.[15] proposed a novel MOMSPSP that the aims of the model were minimizing the total salary of the workforce involved in performing activities, minimizing total completion time of activities, and maximizing the workforce's efficiency on performing skills of activities by non-linear learning curve function. They proposed two hybrid TLBO based algorithms inspired by the multi-objective concept of the MOPSO and MOIWO algorithms to solve the model. The results showed that the MOPTLBO algorithm had better performance in terms of the MID, while the NSGA-II algorithm was the best in terms of the SNS metric. Furthermore, the FSTLBO algorithm was best for the MS and Spacing mean. The results showed that the proposed hybrid FSTLBO algorithm had a better overall performance on solving various instances.[16] dealt with a new variant of MSPSP with respecting partial preemption, in which only a subset of resources can be released during the preemption periods. They proposed a series of heuristic algorithms to solve instances arising from an industrial application. Therefore, they presented a serial greedy algorithm based on priority rules and a flow problem for resource allocation. They introduced a binary tree-based search algorithm and a greedy randomized adaptive search procedure (GRASP) to improve the solutions of the greedy algorithm. Finally, they proposed an extensive neighborhood search (LNS) algorithm integrating exact and heuristic methods. The best solution quality and execution time results were obtained by combining the GRASP algorithm and LNS approach.[17] reviewed and surveyed the literature on scheduling problems under multi-skilled and flexible resources. The paper's primary purpose was to help researchers and scholars enter the multi-skilling experience with a comprehensive overview of existing models and methods and identify new research directions. He reviewed and classified 160 articles published from 2000 to 2020 based on the objective functions, the mathematical modeling, the solving methodologies, and the potential applications. The results showed that the main focus of the existing research in this field had been allocated to project scheduling problems (53.12%), mixed integer programming models (54.2%) and meta-heuristics (28.7%) as solving method, cost (39.4%) as a single objective model (68.6%), and deterministic condition for parameters (85.5%) on the top. It also showed that 68.8% of research regarded a single objective, of which 13.8% and 17.6% of the study have developed models with two and more objectives, respectively.

After reviewing research in RCPSP, MMRCPSP,

TCQTP, and MSPSP, a novel mathematical model for combining TCQTP, MMRCPSP, and MSPSP when project dealing only with staff resources will be presented, which in turn is new.

III. MODEL DESCRIPTION

This section first presents and formulates the mathematical model for MOMMMSPSP, indices, parameters, and decision variables. Afterward, a mathematical model for the related MOMMMSPSP regarding the following assumptions is defined.

Herein, a novel three objective model is proposed to:

- Determine workforce assigned to skills of each activity
- Determine the best possible starting times of all activities
- Determine the best mode of each activity

Herein, an integer linear programming formulation is presented to formulate the problem. The proposed model aimed to optimize three different conflicting objectives, including 1) minimizing the project's total completion time, 2) maximizing the project's total quality, and 3) minimizing the project's total cost. In the following, the major underlying assumptions of the model, indices, parameters, decision variables, and the mathematical model are presented.

A. Most significant assumptions:

- The project's network is defined as an AON network.
- Activities are indexed in a topological form.
- All the required resources are workforce and are always available.
- Performing each activity needs several skills.
- Each workforce has various skills (either has a specialty or does not)
- All the execution times are considered integer.
- Each activity execution's time is an integer, depending on its selective executing mode.
- Activities' setup times and time of assigning resources to the activities are ignorable.
- Interrupting activities during their execution is not allowed (preemption is not allowed).
- Each activity must be performed under one mode during its execution from its potential executing modes, and each mode has its unique duration time and requirement.
- Each workforce performs each skill by defined cost and quality.
- Each workforce cannot perform more than one activity simultaneously.
- Each workforce can be allocated to different activities if those activities are not executed concurrently.
- All allocated staff to different skills in an activity must start and finish that skills simultaneously.
- Performing skills of each activity need several predefined numbers of workforces (depending on its executing mode).
- The workforce allocated to each activity should be assigned to particular predefined skills, and their job should be finished in a specific time.
- The project's total quality is calculated as the weighted average quality of all the staff involved in performing the project's different skills.
- All the staff salary via their assignment in activities calculates the project's total cost.

B. Notations

Indices and sets

n The index of the last activity

A_1 The start node of the project

A_n The end node of the project

K number of skills.

M number of executing mode.

S number of staff members.

A_i ,$\in \{1..., n\}$ set of not preemptive activities of the project.

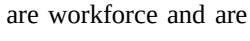
E_k, $k \in \{1..., K\}$ set of skills.

O_m , $m \in \{1..., M\}$ set of modes for performing activities.

R_s, $s \in \{1... S\}$ set of staff members.

G: the project graph defined by (A: activity, E: precedence relation, P: duration).

$(A_i . A_j) \in E$ If there exists a precedence relation between A_i and A_j;

Parameters 

P_{im}: Duration of activity A_i in mode m, $i \in \{1..., n\}$ and $m \in \{1..., M\}$.

$t \in \{0, 1...Tmax\}$:Starting time of project's activities;$T_{max} = \sum_{i=1}^{n} max\ (p_{i1} . p_{i2} . \ldots . p_{iM})$

w_i: Weight of activity;A_i,$\sum_{i=1}^{n} w_i = 1$.

C_{sk}:Salary of staff R_s for executing skill E_k per day.

q_{sk}:Quality of performing skill E_k by staff R_s in the project;[0, 1].

b_{imk}: number of required resources for performing skill E_k during the execution of activity A_i in mode O_m.

r_{sk} =1, if staff member R_s can perform skill E_k; 0, otherwise.

Decision Binary Variables

v_{im} 1, if activity i is done in executing mode m; 0 otherwise.

x_{imst} 1, if staff member s begins to work for activity i in mode m at time t; 0, otherwise.

y_{imsk} 1, if staff member s assigned to activity i in mode m at skill k; 0, otherwise.

C. The proposed mathematical formulation

The developed MOMMMSPSP is now formulated as a multi-objective integer linear programming model:

$$Z_1 = \text{Min} \sum_{m=1}^{M} \left[\frac{\sum_{s=1}^{S} \sum_{t=0}^{T\max} x_{nmst} * (t + p_{nm})}{\sum_{k=1}^{K} b_{nmk}} \right] \quad (1)$$

$$Z_2 = \text{Min} \left\{ \sum_{i=1}^{n} \left[\sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{s=1}^{S} (y_{imsk} * C_{sk} * p_{im}) \right] \right\} \quad (2)$$

$$Z_3 = Max \sum_{i=1}^{n} W_i * \left[\sum_{m=1}^{M} \left[\frac{\sum_{k=1}^{K} \sum_{s=1}^{S} y_{imsk} * q_{sk}}{\sum_{k=1}^{K} b_{imk}} \right] \right] \quad (3)$$

Subject to:

$$\sum_{m=1}^{M} v_{im} = 1; \forall (i) \quad (4)$$

$$\sum_{m=1}^{M} \frac{\sum_{s=1}^{S} \sum_{t=0}^{T\max} x_{imst} * (t + p_{im})}{\sum_{k=1}^{K} b_{imk}} \leq \sum_{m'=1}^{M} \frac{\sum_{s'=1}^{S} \sum_{t'=0}^{T\max} x_{jm's't'} * t'}{\sum_{k'=1}^{K} b_{jm'k'}}; \forall (i, j) \quad (5)$$

$$x_{imst} \leq v_{im}; \forall (i, m, s, t) \quad (6)$$

$$y_{imsk} \leq v_{im}; \forall (i, m, s, k) \quad (7)$$

$$\sum_{m=1}^{M} \sum_{t=0}^{T\max} x_{imst} \leq 1; \forall (i, s) \quad (8)$$

$$\sum_{t=0}^{T\max} x_{imst} * t \leq \frac{\sum_{h=1}^{S} \sum_{t=0}^{T\max} x_{imht} * t}{\sum_{k=1}^{K} b_{imk}}; \forall (i, s, m) \quad (9)$$

$$y_{imsk} \leq r_{sk}; \forall (i, m, s, k) \quad (10)$$

$$\sum_{s=1}^{S} \sum_{t=0}^{T\max} x_{imst} = (\sum_{k=1}^{K} b_{imk}) * v_{im}; \forall (i, m) \quad (11)$$

$$\sum_{s=1}^{S} y_{imsk} = (b_{imk}) * v_{im}; \forall (i, m, k) \quad (12)$$

$$\sum_{m=1}^{M}\sum_{i=1}^{n}\sum_{d=t-p_{im}+1}^{t} x_{imsd} \le 1; \forall (s,t \in Tmax) \tag{13}$$

$$\sum_{t=0}^{T\max}\sum_{m=1}^{M} x_{imst} = \sum_{k=1}^{K}\sum_{m=1}^{M} y_{imsk}\ ; \forall (i,s) \tag{14}$$

$$\sum_{m=1}^{M} y_{imsk} \le 1; \forall (i,s,k) \tag{15}$$

$$\sum_{m=1}^{M} x_{imst} \le 1; \forall (i,s,t) \tag{16}$$

$$x_{imst}\ ,\ y_{imsk}\ ,v_{im} \in \{0,1\};\quad \forall (i,m,s,t,k) \tag{17}$$

The first objective function in Equation (1) minimizes the project's total completion time. The second objective function in Equation (2) minimizes the total amount of salaries that should be paid for the workforce involved in performing the project's various skills in activities. The third objective function in Equation (3) aimed to maximize the project's total quality, defined as the weighted average quality of the workforces allocated to the activities' different skills. Equation (4) ensures that each project activity can only be executed in one mode. Equation (5) considers precedence relations (activity i is the precedent for activity j). Equation (6) guarantees this principle that staff s at time t can start working on activity i in mode m provided that activity i is specified to perform in mode m. Equation (7) enforces that staff s with skill k can be assigned to activity i in mode m provided that activity i is determined to perform in mode m. Equation (8) guarantees that one staff member can be allocated to a maximum of one activity at a time t in the project. Inequality (9) ensures that the entire workforce given for various skills of each activity should concurrently start their job. Equation (10) implies that each workforce assigned to each skill of the activity must be able to perform that skill. Equation (11) guarantees that the total number of staff members assigned to each activity equals the number of staff members with diverse specialties at different skills required for executing that activity. Equation (12) ensures that the total number of staff members at a specific skill allocated to one activity must be equal to the number of staff members required at the considered skill of that activity. Equation (13) guarantees the non-preemptive assignment of workforces to the skills of each activity. In other words, the workforce assigned to a predefined skill cannot be released until the skill is thoroughly performed. Equality (14) describes that if a staff member is assigned to an activity, they should start working on it at only a one-time and must be allocated to one required skill. Equation (15) ensures that any staff with any skill in any activity can be assigned in a maximum of one executive mode. Equation (16) provides that any staff member can start work from the project time horizon in any activity in a maximum of one executable mode. Set of Constraint (17) determines that all decision variables used in the model are binary.

IV. SOLUTION PROCEDURE

One of the most valuable techniques for dealing with multi-objective optimization problems is transforming a multi-objective model into a single one. Since the MOMMMSPSP model is a multi-objective, integer linear programming model where objective functions are entirely inconsistent, we use the [18]L_p*metric* method. According to this method, a multi-objective problem is solved by respecting each objective function separately. Then a single objective is reformulated, which aims to minimize the sum over the normalized difference between each objective and corresponding optimum value.

Our proposed model assumes that three objective functions are Z_1, Z_2, and Z_3. Based on the L_p metric method, the model should be solved separately for these three objective functions. Then the optimal values for these three objectives are Z_1^*, Z_2^*, Z_3^*. Now, the L_p *metric's* objective function can be formulated as Equation (18):

$$LP = \text{Min}\, Z_4 = \left\{ \left[\frac{Z_1^* - Z_1}{Z_1^*} \right]^2 + \left[\frac{Z_2^* - Z_2}{Z_2^*} \right]^2 + \left[\frac{Z_3^* - Z_3}{Z_3^*} \right]^2 \right\}^{\frac{1}{2}} \tag{18}$$

Using L_p metric, objective function, and respecting the MOMMMSPSP model's constraints, we transformed the three objective functions given in Equation (1) – (3) into a single Equation (18) which is integer non-linear programming model; therefore, GAMS software (BARON solver) can efficiently solve this integer non-linear programming, and the optimum point will be gain.

V. COMPUTATIONAL RESULTS

A. Case description (Illustrative numerical sample)

GAMS software was run on a PC with Intel_Core i7 CPU with 8 GB RAM to solve a numerical small-sized sample to verify the proposed mathematical model and illustrate the model's performance. The sample was solved in a computational time equal to 6 minutes and 25 seconds. The sample includes six activities, four staff members, three specialties, and three executing modes. In Figure1, the precedence network of the project has been depicted. Table1shows the number of staff members with specific specialties required for executing each activity at each mode. For example, activity A_3 needs two staff members with $skill_3$ and one with $skill_1$ in $mode_3$ with a processing time of 8 days.

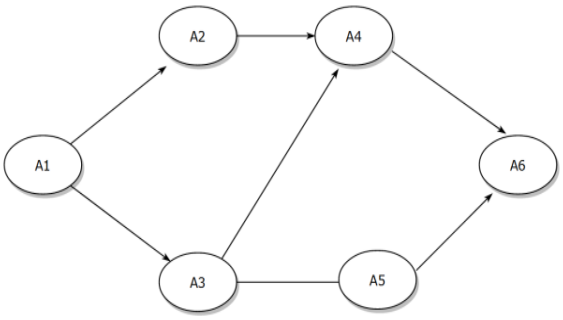


Figure 1. Precedence network of the illustrative example

TABLE 1

The number of staff members with different specialties required for executing each activity to varying skills in each mode and weight of each activity for the illustrative example

Activity	predecessor	W_i	O_1				O_2				O_3		
			p_{im}	E_1	E_2	E_3	p_{im}	E_1	E_2	E_3	p_{im}	E_1	E_2
A_1	_	0.25	10	0	1	0	7	0	1	1	5	1	1
A_2	A_1	0.2	5	1	0	0	4	1	0	1	3	1	1
A_3	A_1	0.2	15	1	0	1	12	1	1	1	8	1	0
A_4	A_2, A_3	0.15	5	0	0	1	4	0	0	1	2	0	1
A_5	A_3	0.1	10	1	0	1	8	1	0	1	4	1	1
A_6	A_4, A_5	0.1	5	0	0	1	3	0	0	1	3	0	1

In Table 2, the capability of each staff member to do skills is given. Table 3 shows the quality of performing each skill by each staff member in the project. Table 4 illustrates the salary cost of executing skills by staff members in each activity per day.

TABLE 2

The ability of each staff member to do a specialty in the illustrative example

r (s, k)	E_1	E_2	E_3
R_1	1	0	1
R_2	1	1	0
R_3	1	0	1
R_4	0	1	1

TABLE 3

Quality of doing each skill by each staff in each activity

q (s, k)	E_1	E_2	E_3
R_1	0.9	0	0.5
R_2	0.7	0.6	0
R_3	0.9	0	0.5
R_4	0	0.7	0.5

TABLE 4

Salary of performing skills by each staff per working day

c (s, k)	E_1	E_2	E_3
R_1	5	0	3
R_2	5	4	0
R_3	5	0	3
R_4	0	5	4

B. Computational Results of multi-objective solution and L_p metric method

In table5, the presented multi-objective model for the MOMMMSPSP is solved by GAMS software, and Optimal values for these three objective functions are obtained as Z_1^*, Z_2^*, Z_3^*.

TABLE 5

The values obtained for three objective functions by GAMS

Z_1^*	20
Z_2^*	224
Z_3^*	0.715

According to the L_p*metric* method, a multi-objective problem converts to a single objective problem, aiming to minimize the sum over the normalized difference between each objective and corresponding optimal value. In table6, the L_p*metric* transformed objective function considering the MOMMMSPSP model's constraints are solved by GAMS, and values for variables are shown. For example, activity A_5 was executed in modeO_3 in four days, staff R_1 performed skill E_1, staff R_2 performed skill E_2, and staff R_4 performed skill E_3.

TABLE 6
The variables values obtained via single objective functions by Lp metric

Activity	Executing mode	start	Assigned staffs			
			R_1	R_2	R_3	R_4
A_1	O_3	0	E_3	E_2	E_1	-
A_2	O_1	5	-	-	E_1	-
A_3	O_3	5	E_3	E_1	-	E_3
A_4	O_2	13	-	-	E_3	-
A_5	O_3	13	E_1	E_2	-	E_3
A_6	O_2	17	E_3	-	-	-

In Figure 2, the obtained scheduling solution, including the assignment of each staff member to each activity at each skill, starting and finishing times of each activity is represented.

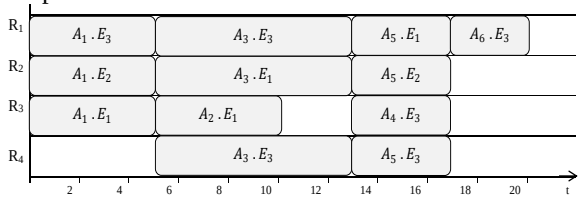


Figure 2. Gantt chart of staff member assignment and scheduling activities for the illustrative example

As seen in the Gantt chart depicted in Figure 2, activity A_1 started at time 0 and finished at time 5, three staff members, including R_1assigned to skill E_3 , R_2 assigned to skill E_2 , and R_3 assigned to skill E_1 . Similarly, the assignment of the other staff members can be interpreted. Considering the staff members' assignment due to executing the project activities as depicted in Figure 2, it could be concluded that all model constraints, including Equations (4)-(17), are respected. In addition, given the optimal scheduling solution obtained by the GAMS and its display in the Gantt chart, it is perceived that the assignment of staff members to project activities exactly follows the problem assumptions with no violation of model constraints.

VI. CONCLUSION

A novel multi-objective multi-mode multi-skilled project scheduling problem with a time cost quality trade-off approach is proposed in this paper. An integer linear programming formulation is propounded for modeling the problem to concurrently optimize the objectives, including (1) minimizing total project completion time, (2) minimizing total salary of the workforce involved in performing activities, and (3) maximizing quality of workforce on performing skills of activities. Then L_p*metric* technique is utilized to find the optimal solution; thus, the proposed model has been solved optimally by GAMS in small-sized. Analyzing the results achieved solving the problem in different sizes draw the following conclusions:

1) Solving the developed mathematical model has created reasonable and feasible solutions for small-sized problems.
2) The optimal solution obtained from solving a mathematical model that was transformed to an L_p*metric* method in small-sized is optimal, reliable also proposed model is firmly NP-hard, and bringing exact solutions is time-consuming.

C. A future extension of this paper is to:

- A researcher can utilize efficient lower bounds resulting from exact methods for solving the developed MOMMMSPSP, leading to better solutions.
- A researcher can apply the presented model for a real situation by utilizing developed heuristic and meta-heuristic algorithms to solve the problem.
- A researcher can consider the model's parameters and variables as fuzzy numbers and develop the model.

REFERENCES

[1] Wiest, J.D., The scheduling of large projects with limited resources. 1962, CARNEGIE INST OF TECH PITTSBURGH PA GRADUATE SCHOOL OF INDUSTRIAL ADMINISTRATION.
[2] Blazewicz, J., JK Lenstra, and A.R. Kan, Scheduling subject to resource constraints: classification and complexity. Discrete applied mathematics, 1983. 5(1): p. 11-24.
[3] Shou, Y., Y. Li, and C. Lai, Hybrid particle swarm optimization for preemptive resource-constrained project scheduling. Neurocomputing, 2015. 148: p. 122-128.
[4] Moukrim, A., A. Quilliot, and H. Toussaint, An effective branch-and-price algorithm for the preemptive resource-constrained project scheduling problem based on minimal interval order enumeration. European Journal of Operational Research, 2015. 244(2): p. 360-368.
[5] Wang, J., et al., A bi-objective robust resource allocation model for the RCPSP considering resource transfer costs. International Journal of Production Research, 2021. 59(2): p. 367-387.
[6] Afshar-Nadjafi, B. and M. Arani, Multimode preemptive resource investment problem subject to due dates for activities: formulation and solution procedure. Advances in operations research, 2014. 2014.
[7] Yuan, Y., et al., Multi-objective multi-mode resource-constrained project scheduling with fuzzy activity durations in prefabricated building construction. Computers & Industrial Engineering, 2021. 158: p. 107316.
[8] Afruzi, E.N., et al., A multi-mode resource-constrained discrete time-cost trade-off problem solving using an adjusted fuzzy dominance genetic algorithm. Scientia Iranica, 2013. 20(3): p. 931-944.

[9] Monghasemi, S., et al., A novel multi-criteria decision-making model for optimizing time–cost–quality trade-off problems in construction projects. Expert systems with applications, 2015. 42(6): p. 3089-3104.
[10] Nguyen, D.-T., et al., Trade-off time cost quality in repetitive construction project using fuzzy logic approach and symbiotic organism search algorithm. Alexandria Engineering Journal, 2022. 61(2): p. 1499-1518.
[11] Sharma, K. and M.K. Trivedi, AHP and NSGA-II-Based Time–Cost–Quality Trade-Off Optimization Model for Construction Projects, in Artificial Intelligence and Sustainable Computing. 2022, Springer. p. 45-63.
[12] Néron, E. Lower bounds for the multi-skill project scheduling problem. in Proceeding of the eighth international workshop on project management and scheduling. 2002.
[13] Montoya, C., et al., Branch-and-price approach for the multi-skill project scheduling problem. Optimization Letters, 2014. 8(5): p. 1721-1734.
[14] Shahnazari-Shahrezaei, P., S. Zabihi, and R. Kia, Solving a multi-objective mathematical model for a multi-skilled project scheduling problem by particle swarm optimization and differential evolution algorithms. Industrial Engineering & Management Systems, 2017. 16(3): p. 288-306.
[15] Zabihi, S., et al., Multi-objective teaching-learning-based meta-heuristic algorithms to solve multi-skilled project scheduling problem. Computers & Industrial Engineering, 2019. 136: p. 195-211.
[16] Polo-Mejía, O., et al., Heuristic and metaheuristic methods for the multi-skill project scheduling problem with partial preemption. International Transactions in Operational Research, 2021.
[17] Afshar-Nadjafi, B., Multi-skilling in scheduling problems: A review on models, methods, and applications. Computers & Industrial Engineering, 2021. 151: p. 107004.
[18] Deb, K., Multi-objective optimization, in Search methodologies. 2014, Springer. p. 403-449.

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