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MILP with Multi-Skilled Workforce and Multi-Mode Performance in RCPSP

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Abstract. Realizing the importance of project scheduling towards the success of an organization, this field has been studied in depth known as resource-constrained project scheduling problems (RCPSP). These problems have since branched extensions including NPV costs and penalty calculations and multi-mode workers that affect the duration and costs of the activities in multi-mode RCPSP (MM-RCPSP). Another extension features a skill requirement for each activity and skill capacities for each worker, referred as multi-skilled RCPSP (MS-RCPSP). Combining these two considerations yields a multi-mode and multi-skilled RCPSP (MM-MS-RCPSP), which has not yet been thoroughly explored in the field of nonlinear programming models. Hence, this study aims to construct a nonlinear optimization model that minimizes the costs of worker assignments and activity completion times given different modes for completion and workers with different skill capacities that would only meet the skill requirements of certain activities. The GAMS formulation of the model yields a plausible optimal solution of 457.54 monetary units with its scheduling approach being realistic and applicable. Linear regression analysis was conducted and returned a strong positive relationship between the activity numbers and incurred costs, which can be adopted by managers to identify benchmarks. With this paper, the study believes to have successfully contributed valuable literature towards the novel extension of MM-MS-RCPSP.

Keywords: RCPSP, NPV, multi-mode, worker assignment, skills assignment

1. Introduction (Use "Header 1" Style)

Generally, minimization of project completion time is the most popular type of objective function in the RCPSP literature. However, the practicality in knowing the most profitable project in a portfolio environment or revenue outcome of a project during the planning stage is much more important to real-life project stakeholders. Since there is a trade-off between cash flows as introduced by [1], the problem of scheduling the activities in a project aimed at maximizing the Net Present Value (NPV) has attracted the attention of most researchers. The proposed idea of NPV by [1] was nonlinear and assumed that there is no limitation of resources. Such was addressed by [2] by modelling an optimal-finder algorithm that involves resource constraints in maximizing NPV. Reference [3] established a two-stage heuristic model and they found that while the difference between the due date and project duration increases, the NPV also improves.

In maximizing the NPV, factors concerning positive or negative cash flows while scheduling the project's activities are considered through multi-mode resource-constrained project scheduling problem (MM-RCPSP). Positive cash flows or inflows are the earnings as the project progresses, while, negative cash flows or outflows are the expenses due to consumption of resources (i.e. manpower, technology, machines) to finish the activity. In this case, cash flows are influenced by activity deadlines, task duration, and resource requirements. Reference [4] proposed an algorithm on which both positive and negative cash flows are considered with limited resources. Afterward, other factors such as uncertainties, payment methods, and discount flows are explored that greatly developed NPV maximization. Reference [5] evaluated the maximization of NPV in fuzzy environment and activity durations are triangular fuzzy numbers, while, [6] considered the uncertainty of environment in maximizing NPV. MM-RCPSP is expressed by [7] through four payment models – lump-sum payment model, payments based on previously finished nodes, payment in

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equal time intervals, and progress payment based on the project milestones. Reference [8] and [9] assumed that cash inflows and outflows occur as its completion time to maximize NPV.

Another notable extension of RCPSP is the multi-skill RCPSP (MS-RCPSP) wherein resources provide workforce skills with various levels and each project activity requires a resource that is equal to or higher than the required skill level. This problem is explored in the literature by involving resource (manpower) limitations which depicts real-world projects through efficient workforce scheduling and rostering. Reference [10] considered the effectiveness of assigned employees while minimizing the make span of the project. The studies of [11] and [12] minimize the total cost of a project with multi-skilled staff assignment problems in labour-intensive organizations. [11] assume the availability of a certain skill level as a model constraint, while, [12] include skill profit as part of the objective. Reference [13] extend the MS-RCPSP by considering a multi-objective model intended to decision-making executives concerning portfolio selections in IT product development. This is the model paper of [14] with the consideration of the learning and forgetting curve of the assigned workforce. Reference [15] integrate project scheduling with task precedence relationships while considering flexible working hours of multi-skilled workforce.

In their paper, each activity requires a set of skills and the activity duration depends on the skillset and number of workers assigned to do the task.

The objective of this paper is to formulate a mathematical model to minimize the NPV costs and penalties of a project in a multi-mode environment. The main contributions of this paper are as follows: (1) cost considerations due to a variety of modes of execution (i.e. shorter duration but with higher expense), (2) skill capacities among workforce and skills requirements per activity (3) manpower as the resource-constrained in a project.

2. Methodology

2.1. Problem Definition

The system to be studied considers the merging of MM-RCPSP and MS-RCPSP in a new extension to be noted as MM-MS-RCPSP. On one hand, the MM-RCPSP refers to the assignment of different modes for the workers so that the completion times of certain activities can be lowered. However, different modes would entail different costs to be paid to the workers assigned to these activities. On the other hand, the MS-RCPSP component refers to the limited ability of the workers to perform activities within their skill capacities. The resource constraints would pertain to the limited workforce that can only be assigned to one activity at any given time. Together, this article aims to formulate a nonlinear programming model with these extensions adopted. This model takes the following conditions and/or assumptions:

- The skill capacities of each worker and each activity are defined, and they can be directly compared.
- The earliest starting time, precedence, costs, and modes are exactly defined in this deterministic model.
- All workers can alter among modes, and the duration each worker takes for each mode is determined to be identical since the minimum skill capacity requirements were met.
- Although some workers with a high skillset can be assigned to activities with low requirements, the duration it takes for the activity to be completed stays the same.
- For an activity to begin, a worker with the minimum required skills must be chosen along with the mode needed to accomplish the activity.
- Although not specifically constrained in the model, each worker would need to accomplish a given activity before moving on to the next one.

2.2. Mathematical Model

To start with any mathematical model, there would be a need to define the indices or sets to be used in the model as well as their set sizes. Furthermore, parameter names would have to be defined for the model to know the values that it would need to consider. Similarly, binary variables are present below with possible values being 1 or 0 needed in mixed-integer problems. Lastly, positive variables are needed to determine critical metrics in the model.

Table 1: Model Nomenclature

Indices	
j	set of activities to be scheduled
m	set of modes available for the activity
t	set of times available to be scheduled
s	set of skills needed for the activities and worker skills
w	set of workers available
n	relative separation of activity index j
Binary Variables	
WT_{mwjt}	1 if worker w is assigned as mode m for activity j during time t; 0, otherwise
WA_{wj}	1 if worker w is assigned to activity j; 0, otherwise
CM_{mj}	1 if Mode m chosen for activity j 0, otherwise
P_{wsj}	1 if worker w is capable of taking skill s of activity j; 0, otherwise
Parameters	
EST_j	Earliest Starting Time of activity j
D_{jm}	Duration needed during mode m for activity j
W_{ws}	Skill s rating of worker w
AS_{js}	Skill s ratings necessary to accomplish activity s
C_{wm}	Cost of worker w to work under mode m
r	Rate of which the NPV will be calculated
MCM_m	Maximum modes that can be chosen throughout the project
Pen_j	Penalty for delayed completion time
System Variables	
z_t	System variable to hold summation of NPVs for costs
S_j	Starting time for activity j
C_j	Completion time for activity j

$$\text{Min } Z = \Sigma_t (z_t) + \Sigma_j (Pen_j * C_j) \quad (1)$$

First, the objective function is shown to simply be the summation of the computed NPV costs of each activity while adding a penalty that increases due to the time of completion of the activity.

$$\text{Min } Z = \Sigma_t (z_t) + \Sigma_j (Pen_j * C_j) \quad (1)$$
$$z_t = \Sigma_j \Sigma_w \Sigma_m (WT_{mwjt} * CM_{mj} * C_{wm} * (1+r)^{-(ord(t)-ESTj)}); \text{ for } \forall t \quad (2)$$
$$W_{ws} + M * (1 - P_{wsj}) \geq AS_{js}; \text{ for } \forall w,s,j \quad (3)$$
$$W_{ws} * WT_{mwjt} \geq AS_{js} - M * (1- WT_{mwjt}); \text{ for } \forall m,w,j,s,t \quad (4)$$
$$\Sigma_m (CM_{mj}) = 1; \forall j \quad (5)$$
$$\Sigma_j (CM_{mj}) \leq MaxCM; \forall m \quad (6)$$

The above constraints refer to the multi-mode requirements of the system being modeled. Equation (2) takes the sum of NPV of mode costs with respect to time spent in each activity. Equation (3) ensures that the worker's set of skills is enough to accommodate for the given activity's skill requirements. Equation (4) notes that the worker skill is enough for activity requirements in each time period. Equation (5) ensures that only one mode will be selected per activity. Equation (6) ensures that the modes to be chosen across all activities would be less than the maximum allowable.

$$\Sigma_j (WT_{mwjt}) \leq 1; \text{ for } \forall m,w,t \quad (7)$$
$$\Sigma_w \Sigma_t WT_{mwjt} \geq D_{jm} * CM_{mj}; \text{ for } \forall m,j \quad (8)$$
$$\Sigma_t (WT_{mwjt}) \geq WA_{wj}; \text{ for } \forall m,w,j \quad (9)$$
$$WT_{mwjt} = 0; \text{ for } \forall m,w,j, (t \geq EST_j) \quad (10)$$

The above constraints were constructed as they belong to multi-skill requirements. Equation (7) ensures that the worker assignments across all the activities would not overlap, causing a worker to be responsible for two activities at the same time t. Equation (8) ensures that the total time a worker has been assigned to an activity meets the necessary duration requirements for the mode chosen. Equation (9) ensures that the worker can only allot time for an activity when the worker can be assigned for that activity. Lastly, Equation (10) ensures that a worker cannot have time units assigned when the activity has not been started.

$$S_j \geq EST_j; \text{ for } \forall j \quad (11)$$
$$S_j \leq ord(t) * WT_{mwjt} * CM_{mj}; \text{ for } \forall m,w,j,t \quad (12)$$
$$C_j \geq ord(t) * WT_{mwjt} * CM_{mj}; \text{ for } \forall m,w,j,t \quad (13)$$
$$S_{j+n} \geq C_j; \text{ for } \forall (j+n) \in \text{precedence subsets} \quad (14)$$

The above constraints are the ones necessary in general RCPSP models. Equation (11) ensures that an activity can only start once the given time period has reached the earliest starting time for it. Equation (12) considers that the starting time for an activity should be less than the sum of all times assigned to the given worker at the corresponding points. Equation (13) ensures that the completion time for the activity should be greater than the sum of all times assigned to the assigned worker at respective times. Finally, Equation (14) ensures that the starting time of each activity with precedence to be greater than the completion time its precedence.

2.3. Data Collection

To validate the model, the activity precedence, corresponding arrival times, and the variety of modes were inspired from [16], while the data regarding workers' skills and activity skills requirements was inspired from [15]. Costing methods in NPV were inspired by [17]. While these data were collected from these sources, their actual values were tinkered to suit the parameters and interactions amongst the elements in the new model.

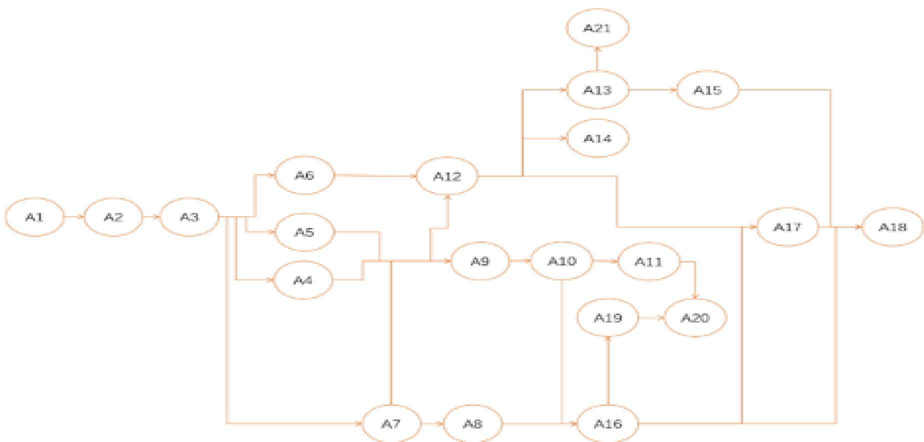

Fig. 1: Precedence Diagram of the Activities to be Scheduled

The precedence of the activities to be used for the model was illustrated above. The direction of the arrows would refer to the activities that require the completion of the origin node before the start of the destination node can be commenced. Hence, with complex and interrelated activities such as what was illustrated, the optimization model can be used to identify the appropriate allocation of the workforce as well as modes of work to determine the best configuration. The idea of precedence is that the deliverables of one activity may serve as the initial materials that the next activity may need. Hence, the value of precedence figures such as the one shown allows the management to identify the possible bottlenecks towards the system.

The workers' skill matrix features three skill capacities (S1, S2, S3) for four workers (W1, W2, W3, W4). The first worker is the standard worker who has an average skillset throughout, while also being the cheapest worker to hire for the activity (S1=0.3, S2=0.8, S3=0.6). The second worker is a better worker who has slightly better skills throughout; hence, this employee requires a slightly higher cost (S1=0.8, S2=0.7), S3=0.5). The third worker may seem to be worse than the second worker on average while also requiring higher pay (S1=0.7, S2=0.8, S3=0.3). This worker was added to serve as a counter-example to see how often the worker will be hired to further validate the model. Finally, the fourth worker is considered to be the best among the bunch with a rating of 0.9 across the board. This worker shall also require the highest pay requirements (S1=0.9, S2=0.9, S3=0.9).

With regards to modes, different modes would entail different duration required for a worker to complete an activity. All workers who have the skills necessary to be assigned to an activity will finish these jobs in 1 time units in mode 1, 2 time units in mode 2, and 3 time units in mode 3. As such, the above are the corresponding costs of the workers to work under each mode. It can be observed that the faster the work, the more costs are incurred. Furthermore, the workers are arranged in increasing order of costs, but not necessarily in skills, which can help garner important insights in the next section. These costs are then subject to a rate of 0.1 or 10%. Moreover, these costs are accompanied by penalty costs of 2 monetary units per day of difference between the completion of a certain activity and time 0. This is done to ensure that the model would be inclined to finish the work as soon as possible while also taking into consideration the costs needed to hire the workers. This value of 2 monetary units was the result of several tests on the model behaviour such that the penalty would not dominate the solution, nor will it affect the model too insignificantly. Lastly, to prevent the model from selecting only a certain mode, only a maximum of six activities can be classified under mode 1 and a maximum of eight can be classified in mode 2. The standard is always mode 3, which features the lowest assignment costs but also the longest duration.

To illustrate this example, if worker 1 was selected with mode 1 for activity 1, then the corresponding contribution of this setup in NPV becomes $5 * (1 + 0.1)^{-1} = 4.5455$. If worker 1 was selected with mode 2 for activity 1, then the setup becomes $3 * (1 + 0.1)^{-1} + 3 * (1 + 0.1)^{-2} = 5.2066$. This along with the penalty costs shall be used to ensure that the model will be inclined to take mode 1 over mode 2 and mode 2 over mode 3. Hence, the presence of a maximum number of activities to be classified into modes 1 and 2 can be justified.

3. Model Validation

To validate the model, the indices, parameters, binary variables, positive variables, objective function, and constraints were coded in the General Algebraic Modelling Software (GAMS). However, due to the size of the model, the formulation was decomposed and ran through iterations of GAMS solver files and Excel solver methods. The results were then analysed in detail to yield interesting discussions. Statistical analysis using linear regression was also used to further the discussions of the paper. These additional insights were retrieved from Minitab Statistical Software.

4. Results and Discussion

Through running the model, an objective function value of 457.54 monetary units was retrieved with the significant findings tabulated below.

Table 2: Primary Results

j	EST	Starting Time	Starting – EST	Ending Time	Mode	Worker	NPV Cost + Pen_j
1	0	0	0	1	1	1	6.55
2	0	1	1	2	1	4	10.61
3	2	2	0	3	1	2	10.51
4	3	3	0	5	2	2	15.22
5	2	3	1	5	2	4	17.82
6	3	3	0	5	2	1	13.91
7	3	3	0	5	2	4	17.82
8	3	5	2	8	3	2	19.09
9	3	5	2	8	3	1	19.09
10	5	8	3	9	1	2	20.54
11	5	11	6	14	3	1	29.74
12	6	6	0	7	1	3	17.59
13	8	8	0	10	2	3	24.05
14	7	7	0	10	3	4	25.10
15	10	10	0	12	2	4	28.01
16	8	9	1	12	3	2	26.11
17	9	12	3	13	1	4	28.32
18	11	13	2	15	2	1	31.51
19	9	12	3	15	3	2	31.58
20	9	15	6	18	3	2	37.19
21	8	10	2	12	3	3	27.16

As observed from the precedence diagram, the bottlenecks of the system would likely be the first three activities as the subsequent activities cannot initiate without all three of these being completed. Since the earliest starting times of the activities that follow (activities 4, 5, and 6) have a relatively early possible starting time. It should not surprise that the model chose to use the limited number of fastest mode (mode 1) to accomplish these activities. It was further identified that activities 10, 12, and 17 are also considered under this importance. For activities 12 and 17, it can be understandable since the former is direct precedence to activities 13 and 14 while the latter appears to be a bottleneck for activity 18. For activity 10, it appears that the main reason for it to be chosen was that it was assigned to activity 16, which means that it needs to finish its activity at hand the soonest before another can be chosen. For the second fastest mode, it was observed that activities 4, 5, 6, 7, 13, 15, 18, and 21 were chosen. It can be observed that activities 4, 5, 6, and 7 belong to the earlier precedence, which meant that these can become major bottlenecks to the system but are not as important as those in the fastest node. For activities 13, 15, 18, and 21, it appears that the system is simply trying to smooth the irregularities in the assignment of work to reduce the NPV costs and penalties of the system. Furthermore, it was determined that the maximum capacity of modes 1 and 2 were used, which indicates the desirability of those modes in the system. Lastly, the activities that were not mentioned were all classified under mode 3 by the model as they appear to yield the least amount of benefit towards the system.

It was observed that the assignment prioritizes worker 1, followed by worker 2, worker 3, and worker 4. However, there were some instances when only worker 4 can meet the skill requirements of the activity such as activities 2, 5, 7, 15, and 17. The only case when worker 4 was chosen but other workers are capable is in activity 14 with worker 2. Observing the results of the model, it appears that worker 2 has not yet completed the activity that it was assigned to do; thus, the model was justified to pick worker 4. Similarly, although worker 3 is placed as one of the less efficient workers in terms of cost, the employee was still chosen for activities 12, 13, and 21. With another observation of the model, it can be seen that worker 3 was only chosen since other workers were still in the process of completing the activities they are assigned. With regards to cause and effects, it appears that there is no relationship between the activity and mode assigned, the activity and the workforce assignment, and the workforce assignment and mode assigned since they yielded 20.49%, 0%, and 0% in adjusted r-square metrics.

If the working hours of the workers are analysed it can be observed that with the maximum end time of the activities being 18 time units, workers 1, 2, 3, and 4 were serving for 11, 16, 5, and 11 time units, respectively. This is equivalent to 61.11%, 88.89%, 27.78%, and 61.11%, respectively. This meant that in terms of utilization, worker 2 was hired the most. This can be due to the fact that out of the 21 activities available, worker 2 can serve all but 6 of these activities. This is true while worker 1 is unable to serve 11 out of the 21 and worker 3 is unable to serve 9 out of the 21. Although worker 4 has the ability to service any activity, the advantage of worker 2 is in costs, which meant that given an activity that both worker 2 and worker 4 are capable and free, the model will likely choose worker 2. As it was mentioned, the skill capacities of worker 3 were intentionally given, and it shows in the model that this worker only worked 27.78% of the time out of the entire work period. Throughout the run, worker 1 would have been the first to be assigned, but because of the limited number of activities that can be assigned, the utilization of the worker was also affected. Thus, these findings help substantiate the validity of the model.

Comparing the differences of the starting times and the EST, it appears that the model has done a good job in managing the worker and mode assignments since it was observed that 9 out of 21 activities, or around 42.86% had 0 lag time from the earliest time an activity can start. Only an average of 1.52 time units of delay was observed per activity, which may be representative of good performance since eliminating lag time is unlikely due to how some of the workers can get occupied with tasks and how some precedence requirements would interfere with a better schedule. With regards to the NPV costs with penalty, it appears that the model cannot be relaxed since the decimal values prevent other solutions from becoming optimal. Hence, these results would be dissimilar to other RCPSP models. Moreover, since they appear to be in an increasing trend, a linear regression analysis can be conducted below to determine its possible implications.

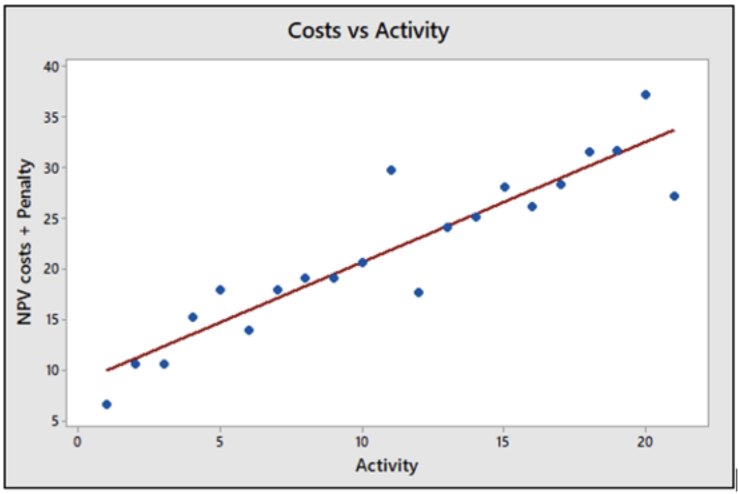

Fig. 2: Costs vs Activity Linear Regression

Using the tabulated costs, a linear regression of the costs incurred as the activities increased can be determined. Through this analysis, an adjusted r-square value of 83.94% was retrieved, which suggests that there exists a strong relationship between the activity that has entered the system and the costs that can be incurred. The following is the equation from the regression analysis.

$$Costs = 1.192*Activity + 8.68 \quad (15)$$

It appears that the activities are subject to around 8.68 worth of monetary costs regardless of the order the activity was taken. Furthermore, it was observed that as the activity number increases, the costs are likely to increase by about 1.192 monetary units. One of the implications includes that this can be used to predict the costs that can be incurred as the number of activities would be increased. It must be noted that the model validation only considered 21 activities in this RCPSP due to software limitations to run the optimization model. Hence, these types of models may no longer be applicable to more complex systems. With this finding, however, the management can consider implementing a smaller model similar to the methods used in this paper to retrieve data that can be run in a regression analysis to give a ballpark figure of the costs to be incurred by the system to guide the project scheduling activities of the organization by using the estimated costs as a benchmark. This can enable the company to set more realistic targets for the organization that would set empirical standards that can both ease the headaches of the management and please the workers regarding their activity assignments. However, there are limitations to this method, which assumes that that similar modes, skills, resources, limitations, and network complexity of precedence would govern the activities that will be added to the system. Furthermore, for these project scheduling problems, it is possible for one delay to snowball and affects the entire system. Hence, this can only be effectively applied if one fully understands the model formulation as well as the statistical analyses that follow.

5. Conclusion and Recommendation

Due to the economic implications of implementing appropriate project scheduling procedures, the RCPSP was conceptualized to solve related issues. Due to the complex nature of the problem in the real-world scenario, different extensions of the problem were explored according to the different needs, wants, and priorities amongst organizations. One of these includes the MM-RCPSP, which considers the possibility of assuming different modes towards a certain activity that would have corresponding costs and/or duration implications. Another includes the MS-RCPSP, which is concerned with workforce assignment that is bounded by the skill requirements of each activity. Although these types of problems are mainly discussed separately, this paper attempts to combine them by introducing a mixed-integer nonlinear programming model that can be helpful towards the management.

The system was first defined in a problem definition statement including conditions and assumptions that will dictate the behaviour of the model. The indices, parameters, binary variables, and positive variables were then defined and delineated to facilitate understanding of the mathematical model. The model was then formulated with a clearly defined objective function and constraints that were divided according to their predominant nature. The parameters were then also determined as well as the rationale for certain configurations. These items were then coded and modelled in GAMS, while subsequent results were analysed in Minitab.

The results of the model regarding the behaviour of the decision variables were observed to be consistent with logical reasoning. The clear bottleneck activities of 1, 2, and 3 were quickly identified by the model to require the most expensive and fastest mode. The other bottleneck activities like 10, 12, 17 were more unnoticeable. With regards to the second-fastest mode, the activities to be classified under this cannot be easily determined by simple analysis. Judging how the variables interact with each other it can be said that the optimal solution shown is generally on the right track. The analysis on the worker assignments seems to have been accurate as well since the solutions tend to follow the logic of which they have been constructed. It was further determined that there exists no relationship amongst the activity, workforce assignment, and mode assignment. The utilization times of each worker from 1 to 4, being 61.11%, 88.89%, 27.78%, and 61.11% can be justified since worker 2 has the second-best skillset while also being more cost-friendly than worker 4. The low utilization of worker 3 was simply a consequence of the weaker skillset compared to worker 2 while also being more expensive, while worker 1 would have always been picked when available if not for its skillset being limited to be capable of fewer activities.

Comparing the earliest starting times with the actual start times, it was determined that only 9 out of 21 or 42.86% of the activities had 0 lag times, while the average of 1.52 time units was observed as the difference. This may indicate that the model has been effective in minimizing unwanted costs. Linear regression analysis was further conducted on the tabulated costs, which revealed that the activity numbers have a strong relationship with the costs, and they can even be formulated as equations. As such, this implies that the management can first solve MM-MS-RCPSP in small-scale models before retrieving relevant to conduct statistical analysis. However, this method may only be applicable in systems where the additional activities would exhibit highly similar properties with existing ones in the model.

Through this endeavour, the research is believed to have been successful with the formulation of a novel model that seeks to allocate the appropriate workforce with the necessary skills required for every activity while considering the different modes the workers can take to minimize costs of the project. Although the validation procedures of this endeavor have been limited by software requirements, the paper still proposes a novel mixed-integer nonlinear programming model towards the understanding of the relatively new extension referred to as MM-MS-RCPSP. As business organizations and processes involved increase in complexity, the need to formulate models such as this to facilitate project management will continue to be more important towards ensuring profitability, efficiency, and overall success. Future researchers can consider possibilities in simulation of such models to further augment findings relevant towards the improvement of such assignments in addition to retrieving real-life data to observe the practical applications of these methods first-hand.

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