CIV E 601 TERM PROJECT

Group 7

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1 INTRODUCTION

Per the 'Term Project Statement and Specifications' document (Bayesteh and Lu 2023) uploaded on e-class, Group 7's understanding is that project management approaches are required to assist in the planning and scheduling of multiple projects within a specified time frame considering resource constraints.

Two assignments have been specified in the 'Term Project Statement and Specifications' document; one with 85 projects of differing durations, sites, ready dates, deadlines, and assigned priorities (Assignment A), in addition to another with 20 projects in which contracts stipulate payment penalties and liquidated damages (LDs), should delays be incurred past the completion deadline (Assignment B). Both assignments require the scheduling of as many projects as feasible and practical, in the best interest of the client organization, per deadlines and priorities in Assignment A, and to avoid or minimize potential financial, contractual, and legal consequences per Assignment B.

In Assignment A, projects provided form a portfolio of municipal drainage and water infrastructure initiatives, involving 3 categories (Bayesteh and Lu 2023) of projects as outlined below:

- **Client-demanded projects** for new infrastructure installations or infrastructure repairs.
- **Prioritized projects** that are assigned a priority index corresponding to the risk associated with infrastructure defects, dysfunctions, and other damages preventing normal operations.
- **Emergency projects** requiring immediate response to address significant client impacts to drainage and water service (i.e. collapsed or broken pipes, sewer backups, lost services).

2 APPROACH

2.1 Project Understanding

Further research and discussion following the initial project updates has yielded a deeper understanding of Assignment A as posed by the term project. Per the information provided, it is understood that a solution is desired to address a Resource-Constrained Multi-Project Scheduling Problem (RCMPSP) (Zheng et al. 2013), in which a portfolio of projects is scheduled, and project implementation requires sharing organizational resources amongst multiple projects with differing priorities. Constraints and prescribed timelines limit the projects that can occur within specific time periods and management methods are required to allocate resources and schedule projects within a portfolio.

Regarding Assignment B, Group 7's objective is interpreted as solving a RCMPSP to minimize liquidated damages (LDs) and other delay costs. This problem is applicable to industry as firms simultaneously manage a portfolio of projects with competing resources, differing completion dates, and delay penalties (Lawrence and Morton 1993).

2.1 Project Plan

To address the problem posed in Assignment A and B, Group 7 has implemented a phased approach based on the term project deliverables, in addition to the timelines specified by the class instructor and Teaching Assistant (TA):

Phase 1 (October 1, 2023 to October 15, 2023)

Scope of Work:

- Initial meeting to review 'Term Project Statement and Specifications' document and establish project scope.
- Conduct a literature review to determine applicable methods/techniques for multi-project scheduling/planning.
- Development of deliverables to be submitted to the instructor and TA.

Deliverables:

- Preparation and submission of Project Update 1 by October 11, 2023.

Phase 2 (October 16, 2023 to November 5, 2023)

Scope of Work:

- Selection of analytical method(s) based on the literature review conducted to address questions related to both assignments.
- Development of deliverables to be submitted to the instructor and TA.

Deliverables:

- Preparation and submission of Project Update 2 by November 2, 2023.

Phase 3 (November 6, 2023 to December 1, 2023)

Scope of Work:

- Execution of appropriate analytical method(s), including creation of an application(s), if required, to schedule projects in both assignments.
- Development of deliverables to be submitted to the instructor and TA.

Deliverables:

- Finalized project schedules outlining projects to be carried out, in addition to the applicable timelines.
- Preparation and submission of the final presentation by November 22, 2023.
- Preparation and submission of the final report by December 1, 2023.

Work Distribution

In maximizing group member participation in the project, the following table summarizes the contribution of each member.

Table 1: Group Member Work Contribution

Group Member	Project Contribution
Lily Ren	• Assignment A literature review, solution development, solution implementation, and validation. • Preparation of project updates I and II. • Development of relevant Assignment A presentation slides, recording of Assignment A slides in video presentation. • Video presentation compilation and editing.
Suzana Trac	• Assignment A and B literature review, solution development. • Preparation of project updates I and II. • Development of relevant Assignment A presentation slides, recording of Assignment A slides in video presentation. • Overall final project report drafting, compilation, and formatting.
Haoran Liang	• Assignment B solution development and solution implementation. • Development of relevant Assignment B presentation slides, recording of Assignment B slides in video presentation. • Drafting of Assignment B information in overall final project

		report.
Owen Zhao	•	Assignment B solution development and solution implementation.
	•	Development of relevant Assignment B presentation slides, recording of Assignment B slides in video presentation.
	•	Drafting of Assignment B information in overall final project report.

3 SOLUTION

3.1 Literature Review Summary

There are numerous methodologies to solve RCMPSPs. RCMPSPs are considered NP-hard problems in the strong sense (Villafáñez et al. 2019), indicating there are no known algorithms for finding optimal solutions in polynomial time. Researchers and industry experts have proposed applying linear techniques, including integer linear programming (Toffolo et al. 2016) or mixed integer linear programming (Kyriakidis et al. 2012) to address the problem. Zheng et al. proposed an algorithm derived from a bi-objective model considering project priorities and uncertain activity durations (Zheng et al. 2013). Villafáñez et al. developed a market-based algorithm to allocate resources with opportunities for a project manager to assign project priorities within the portfolio (Villafáñez et al. 2020).

Priority rule (PR) heuristics are of particular interest due to their criticality in solving large problems, as well as their simplicity and relatively fast implementation speed (Browning and Yassine 2010). In addressing multi-project scheduling, researchers have disagreed about which PR provides the best performance, though prioritizing scheduling of projects/activities with minimum slack first (MINSLK) have typically performed well (Cohen et al. 2004). However, Kurtulus and Davis, upon analyzing multiple PRs, including prioritization based on the shortest activity from the shortest project (SASP), minimum total work content (MINTWK) considering duration and resource requirements, and maximum total work content (MAXTWK), determined that scheduling based on SASP will minimize total project duration (Kurtulus and Davis 1982).

In a following study, Kurtulus evaluated other PRs including maximum duration and penalty costs (MAXDUP), penalty costs and minimum slack (SLKPEN), and determined that prioritization based on projects/activities with the highest cost penalty (MAXPEN), produced minimum overall delay penalties (Kurtulus 1985). PRs can also be combined with decision making methods as illustrated in Singh's presentation of a hybrid algorithm to solve RCMPSPs based on PRs and the analytic hierarchy process (Singh 2014).

To address penalty costs specifically related to late activity/project completion, Lawrence and Morton adapted a slack-based heuristic using resource prices to calculate marginal delay costs (Lawrence and Morton 1993). This method has been proven to provide schedules with significantly lower average costs compared to other proposed heuristics for weighted scheduling problems (Lawrence and Morton 1993). Assuming that a project's duration is equivalent to its cost, the project priority, P_{ij}, as calculated by Lawrence and Morton (Lawrence and Morton 1993) is summarized below:

$$P_{ij} = \frac{W_i}{p_{ij}} exp\left(-\frac{l_{ij} - t}{k\bar{p}}\right) \quad (1)$$

Where W_i is the penalty cost for each time unit a project is delayed by, $\bar{p}$ is the average durations of all projects, p_{ij} is the project duration (which is assumed to be proportional to crew usage), l_{ij} is the latest starting date for a project prior to incurring delay costs, *t* is the date currently being scheduled, and *k* is an empirically determined planning parameter (Lawrence and Morton 1993).

The PR indicated above serves as a cost-benefit rule comparing the estimated cost of delaying a project to the resource savings realized by delaying its start (Lawrence and Morton 1993). A project that is not started by l_{ij} will incur delay costs of W_i per day (Lawrence and Morton 1993). Projects with positive slack ($l_{ij} - t > 0$) may be unable to be scheduled prior to l_{ij} due to resource constraints, and are charged a discounted delay look-ahead penalty $W_i exp\left(-\frac{l_{ij}-t}{k\bar{p}}\right)$ that decays to 0 as slack goes to infinity (Lawrence and Morton 1993). In this scenario, opportunity costs, p_{ij}, assumed to be proportional to the project duration, balance the potential delay penalties by representing the cost of resources required to complete project *ij* (Lawrence and Morton 1993).

However, a key drawback of this PR is that it only provides consideration for penalty costs associated with each time unit of delay and does not account for LDs that are not a function of delay time.

Projects can also be scheduled to account for uncertainty through reactive project scheduling, involving modification of the baseline schedule when unanticipated disturbance events occur during project execution (Peng et al. 2023). Disturbance events can include changing activity durations, resource requirements, and resource availabilities, in addition to the arrival of new projects (Peng et al. 2023). Reactive multi-scheduling problems have not been the topic of much research, and most papers employ solutions similar to that of a single-project scheduling problem, in which adjustment cost of the baseline schedule is minimized (Wang et al. 2019) (Wang et al. 2020). Moreover, these methodologies do not consider the addition of new projects.

Reactive scheduling methods can be classified into 4 categories:

1. Complete rescheduling, where a schedule is completely regenerated when disruptions occur (Van de Vonder et al. 2007). The scheduling approach used to generate the baseline schedule is now used to generate a new schedule on a modified project/portfolio network (Van de Vonder et al. 2007).
2. Application of an early start policy at the disruption point, while maintaining resource allocation decisions made in the baseline schedule, as reflected in the resource flow network (Van de Vonder et al. 2007).
3. Activity/project-based PRs to decide which activity/project to schedule (Van de Vonder et al. 2007).
4. Scheduling activities/projects to minimize the weighted earliness-tardiness penalty costs of the project/portfolio (Van de Vonder et al. 2007).

Peng et al. developed a model to balance tardiness penalty and adjustment costs of the baseline schedule in a two-stage reactive multi-project scheduling method (Peng et al. 2023). The first stage involves full rescheduling upon new project arrival and the second stage involves minimizing the adjustment cost of the baseline schedule (Peng et al. 2023).

3.1 Project Methodology

Assignment A

Given that all projects within the portfolio are known prior to scheduling, the problem in Assignment A represents a static RCMPSPP (Lawrence and Morton 1993) problem. Based on the information provided in the 'Term Project Statement and Specifications' document (Bayesteh and Lu 2023), the following constraints and assumptions are imposed upon the portfolio of projects in Assignment A:

- Assignment A is different from the norm where the priorities of projects, P_{ij}, have already been provided. Therefore, PRs need not be applied to assign project priorities.
- Predecessor-successor relationships are not provided for projects, and as such, they can be considered non-precedence constrained projects. We can assume each project in the portfolio as an activity in one mega-project.
- The date in which the project site becomes available and deadlines for each project can be assumed to represent both the Early Start (ES) and Late Finish (LF) dates for each project. This allows for the calculation of slack (SLK) through the following equation:

$$\mathrm{SLK} = \mathrm{L}S - \mathrm{ES} - \mathrm{Duration} \quad (2)$$

where ES represents the earliest start time of a project, LS represents the latest start time of a project, and duration is the project duration. Project prioritization based on slack priority can be considered where an index is determined by slack divided by max slack (Zheng et al. 2013):

$$\text{Slack Index} = \frac{\text{Slack}}{\text{Max Slack}} \quad (3)$$

- Resource availability and capacity poses a constraint on project scheduling, as there are only 8 crews available to complete the project work. It is assumed that each crew can complete at most one project at a time, projects cannot be split between crews, and travel time between the sites do not need to be considered in the scheduling duration.
- A standard 8-hour per day, 5 days per week working calendar is assumed for all activities in A.1, noting that October 9 is a statutory holiday with no work occurring. In addition, the 3-week planning horizon specified in A.1 is taken to start on October 2 and end on October 23.

Based on Browning and Yassine (Browning and Yassine 2010), a static RCMPSP is evaluated as follows:

- A set of projects is defined as $l = 2,..., L$.
- Each project consists of $i = 1, \ldots, N_l$ activities.
- Each activity's duration is specified as d.
- Each activity requires r_{jk} units of resources of resource type $k \in K$ during its duration.
- Resource k has a renewable capacity of R_k.
- At any time, if a set of non-precedence constrained activities requires more than R_k for any k, then some activities will be delayed.

Assignment A has a $l = 85$ projects in a portfolio and does not provide activity details for each project. Considering A.1 as illustrated in the table below, $\Sigma R_k = 118$ days of resource capacity is available for 8 resources (crews) over the course of a 3-week planning window. However, the project durations are summed at $\Sigma d = 150$ days before the October 23 deadline. This means some projects will be delayed and will be unable to meet the October 23 deadline. To allow for the incorporation of all projects in the scheduling exercise as per Question 2, Group 7 will explore extending the planning horizon or extending working hours from 8 to 10 hours per crew per day.

Table 2: Assignment A Resource Allocation Bar Chart

Resource Allocation Bar Chart																							
Day(s)		1	2	3	4	5				6	7	8	9			10	11	12	13	14			15
October		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Cr_01	15																						
Cr_02	15																						
Cr_03	15																						
Cr_04	14																						
Cr_05	15																						
Cr_06	15																						
Cr_07	14																						
Cr_08	15																						

For Question 2 of Assignment A, $\Sigma R_k = 150$ days of resource capacity is available over the course of a 4-week planning window. The project durations are summed at $\Sigma d = 191$ days for all

85 projects before the October 28 deadline. This means that some projects will be delayed even if the planning horizon is extended for one more week. Assessing the working hours required to complete all 85 projects yields a total of 1,528 hours assuming 8 hours of work per day. As such, additional work is needed to determine an optimal solution to schedule all projects.

Assignment A – Manual Solution

Group 7's goal is to employ a simple, elegant, and practical method to optimize the amount of high priority projects completed within the 3-week duration, while minimizing delays per A.1, and extend the methodology to schedule the remaining projects in A.2. Noting that project selection and timelines specified by the date ready and deadline dates are key factors in determining which projects will be scheduled, the objective of the planning exercise is to develop a feasible schedule that will (1) optimally allocate constrained resources to select projects within the 3-week period as per A.1, and (2) while reducing overall portfolio duration for A.2.

The project prioritization considerations implemented for Assignment A are as follows:

- First, sort projects based on the assigned priority index.
- For all projects with the same priority, consider projects with minimum slack per Equations (2) and (3).
- For all projects with the same priority and slack, consider projects with the earliest deadline.
- For all projects with the same priority, slack, and earliest deadline, consider projects with the earliest start date, as determined from the site ready date.

Adapting the scheduling process as implemented by Villafáñez et al. (Villafáñez et al. 2019) and incorporating the factors outlined above, the following flowchart outlines the implementation of prioritization considerations for A.1 and A.2:

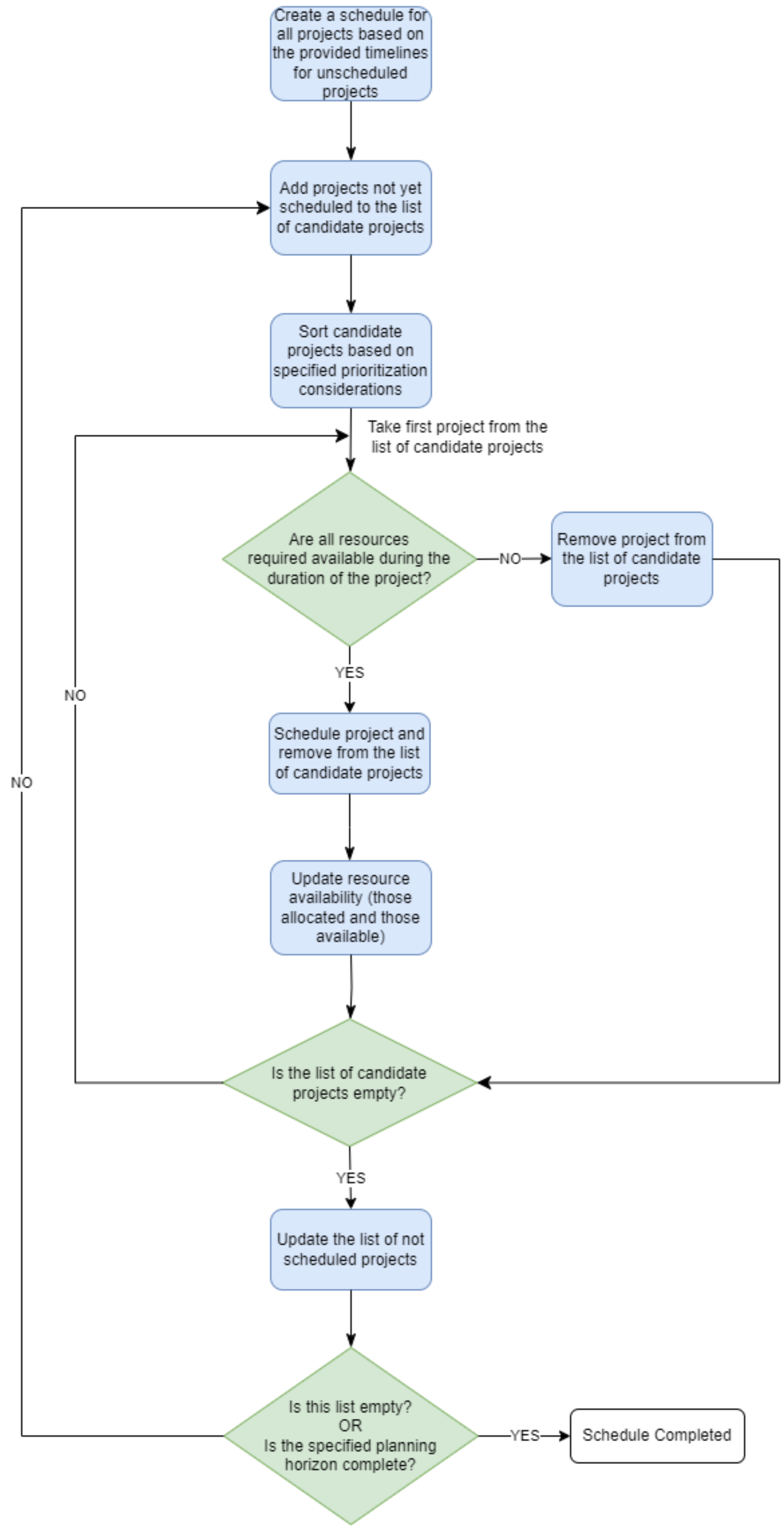

Figure 1. Scheduling Process for A.1 and A.2

In the context of A.1, the scheduling process involves isolation of projects with deadlines on or before October 23, then sorting the projects based on priority, slack index, deadline, and site ready date, as described above. Crews are then manually assigned per these considerations, while prioritizing high priority projects. For A.2, projects that were not scheduled in A.1 are manually added to the schedule according to the same prioritization considerations. To facilitate ease of scheduling, in lieu of approving overtime, and considering that no delay penalties are stipulated in the project specifications, the planning horizon is extended to accommodate planning of remaining projects. The scheduling process' objective is to minimize the number of delayed projects where possible.

The scenario posed by A.3 is understood to be a reactive scheduling problem in which the baseline schedule (previously generated in Questions 1 and 2) is updated due to the addition of a new project. For simplicity, techniques involving rigorous mathematical computations are not employed and the complete rescheduling method is utilized to solve the problem. Rescheduling is done by following the methodology utilized to address Questions 1 and 2 on a modified project network in which projects that are already finished by October 10 are omitted from the original project network (Van de Vonder et al. 2007). The main objective for A.3 is to update the baseline schedule to minimize adjustments while accommodating inclusion of the emergency project. This is achieved by manual insertion of the emergency project on October 10, and rescheduling lower priority project(s) to allocate resources to the emergency project.

Constraints and assumptions applicable to solving A.3, as per typical complete rescheduling solutions (Van de Vonder et al. 2007), are listed below:

- Projects that have already started by October 10 but are not yet completed are kept in the network with the projected remainder of the project duration as their planned duration. This assumes that the remaining duration is known when a project is not completed at a particular time (Van de Vonder et al. 2007).
- The emergency project is assigned the highest priority (priority 1) and is assumed to be able to occur concurrently with other projects.

- Projects currently in progress on October 10 can be delayed to accommodate resource allocation to the emergency project, with no additional time required for start-up and remobilization should the project be completed at a later time.

Assignment A – Microsoft Project Solution

As a means of validating the results from the manual scheduling process, in addition to providing a benchmark to compare project results, Microsoft Project 2019 is employed to generate a resource-balanced schedule for Assignment A questions.

For Questions 1 and 2, one crew is assigned an 800% planning capacity over the planning horizon to account for 8 crews, except for 600% capacity on October 23 as Crew_04 and Crew_07 have an availability of 14 days compared to all other crews' 15-day availability. Assigned project priorities are converted from $Pij = 1, 2, \ldots, 5$ to priority weightings of 900, 800, …, 500 in increments of 100, respectively, in Microsoft Project. The levelling order of 'priority, standard' is utilized to prioritize unscheduled projects based on the priority field first, then examines predecessor dependencies, slack, dates, and constraints.

The emergency project in A.3 is included with a priority of 1000 and a 'start no earlier than October 10' constraint prior to resource levelling. This ensures the start of the emergency project will not be delayed past October 10 as resource levelling based on priority cannot move a project with an assigned priority weight of 1000. The output of this method can be seen in Figures 3, 4, and 5.

Assignment B

In Assignment B, Group 7 aims to schedule multiple resource-constrained projects with the goal of minimizing LDs and other delay costs to maximize organizational profitability. The resource slack-based PR developed by Lawrence and Morton (Lawrence and Morton 1993) as discussed in the literature review is referenced due to its ability to weigh project importance and reduce delay costs. The priority index calculation as represented by Equation (1) can be adapted to incorporate LDs in a manner analogous to the inclusion of delay costs:

$$P_{ij} = \frac{W_i}{p_{ij}} exp\left(-\frac{l_{ij} - t}{k\bar{p}}\right) + \frac{F_i}{p_{ij}} exp\left(-\frac{m_{ij} - t}{k\bar{p}}\right) \quad (4)$$

$$F_i = LD_i - CP_i \quad (5)$$

Keeping the same variable definition as outlined in Equation (1), Equation (4) also introduces new variables where F_i represents the difference between LD, LD_i, and contract price, CP_i, of project i, the term m_{ij} denotes the latest starting date for a project before the LD is incurred. For this problem, k is taken to be 12 as literature has indicated this value results in best overall performance (Lawrence and Morton 1993).

Constraints and assumptions considered in solving Assignment B are derived from the problem statement and is described per the following:

- The LD for each project can be applied in full when a project is not completed past its deadline. Delays past the due date will incur the stipulated delay penalties per day.
- While there is no information provided on how much of the contract price is consumed by a project delayed past its deadline date, for the purposes of determining overall project profitability, Equations (4) and (5) consider project LDs in comparison to the overall contract price. This is considered to provide a more comprehensive assessment of the monetary value of the project, in comparison to considering delay penalties only.
- Similar to Assignment A, predecessor-successor relationships for projects to be scheduled are not provided, and as such, each project is considered to be independent from the others.
- Resource constraints are imposed by there being only 3 crews with specified capacities to complete the work. While the problem states that each project only requires one crew, it is assumed that crews can be split among different projects. Project work is also assumed to be continuous with no interruptions, and travel time between the sites do not need to be considered in the scheduling duration.
- No specific dates are provided in Assignment B for scheduling of the 3-week planning window. As such, an arbitrary 3-week calendar starting from the 1st day of a month and ending on the 19th day is used in this problem. It is assumed that a standard 5-day work week applies, with no statutory holiday or day-in-lieu occurring in the 3-week planning

window that would add additional non-working days (i.e. there is a total of 15 working days in the 3-week period).

The solution workflow employed in Assignment B is outlined in the flowchart below. Note that Project IDs as provided in the problem statement are simplified and referred to as projects #1 through #20 (i.e. Project ID 1001 is referred to as Project #1 and Project ID 1002 is referred to as Project #2, etc.) for ease of result presentation. A MATLAB algorithm (Appendix A) is developed to calculate priority indices, P_{ij}, to facilitate priority-based sorting.

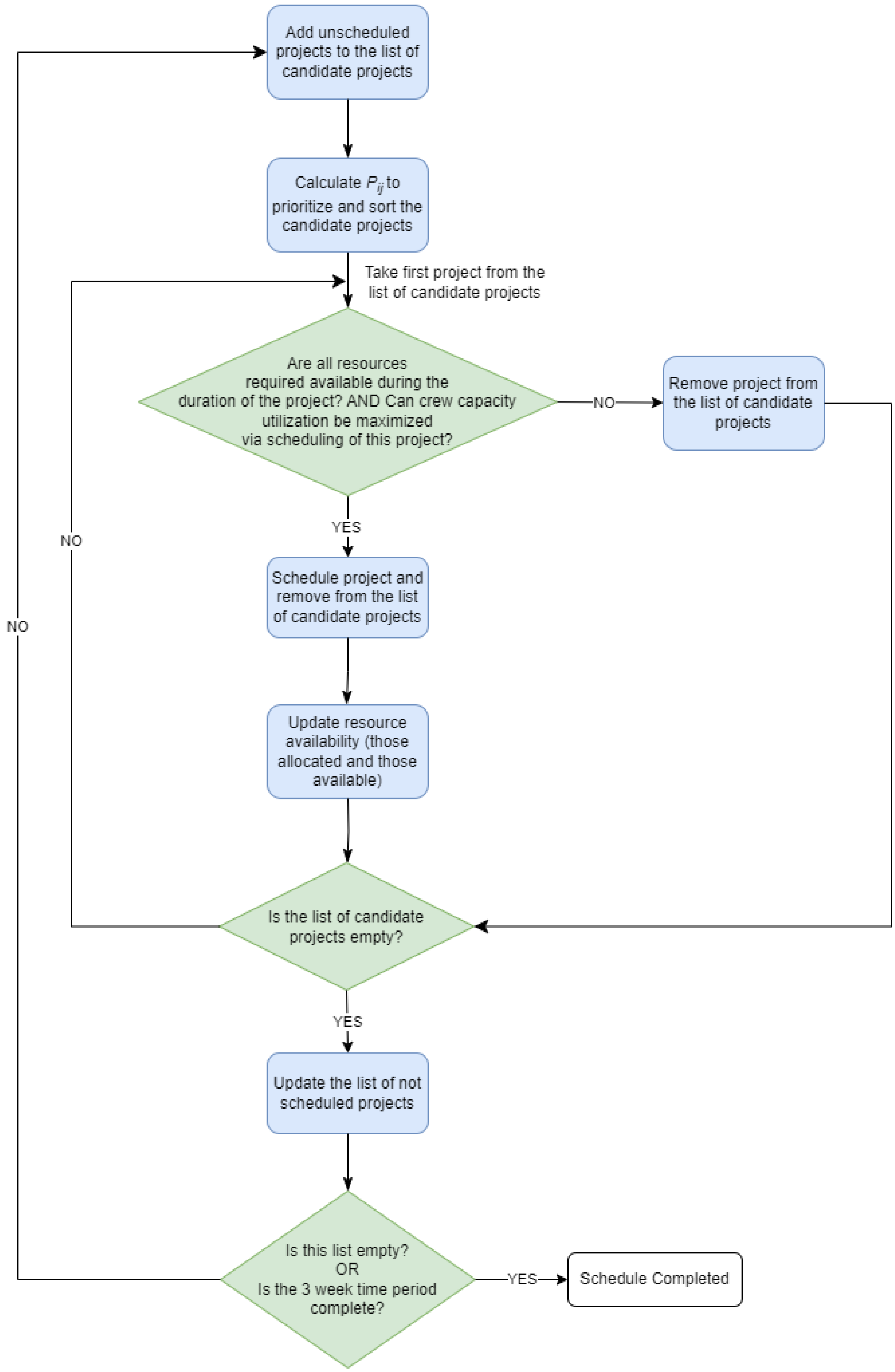

Figure 2. Scheduling Process for Assignment B

User interpretation of priority indicators in conjunction with resource availability is utilized to enable crew utilization maximization. For instance, consider the following scenario of scheduling the latter half of Crew_03, with the present scheduling day being Day 9. The remaining projects in the candidate list for this scenario are presented in the table below.

Table 3: Unscheduled Assignment B Projects in Candidate List for Crew_03 on the Latter Half of Day 9

Project ID	Duration (Days)	Priority Index, $\boldsymbol{P_{ij}}$
14	3	1152.08
12	4	1027.49
5	4	1019.49
2	5	957.60
1	4	880.14

In this scenario, the highest priority project for scheduling based on index only would be Project #14. However, given that the current residual capacity of Crew_03 is 9 days, scheduling Project #14 on Day 9 would result in suboptimal utilization of Crew_03. Observation of the other remaining projects identifies alternative projects (Project #12, #5, #2, and #1) with durations of 4 or 5 days. Scheduling Project #2, as well as one of the projects with a 4-day duration will enable full utilization of the crew. Consequently, in this case, Project #14 should not be given scheduling priority. Instead, priority should be accorded to those projects with durations of 4 and 5 days that also possess relatively high P_{ij} values.

4 RESULTS

4.1 Assignment A

As shown below, the scheduling results for all Assignment A questions are displayed for both the manual and Microsoft Project approaches. The manual solutions for A.1 and A2 in Tables 4, 5, and 6 are colour coded based on the priority index P_{ij}. With red being P_{ij} *= 1*, orange being P_{ij} *= 2*, green being P_{ij} *= 3*, blue being P_{ij} *= 4*, and purple being P_{ij} *= 5*. In the manual approach for A.1 as shown in Table 4, all projects with a deadline on and before October 23 were scheduled for P_{ij} *= 1 and* P_{ij} *= 2*.

Table 4: Assignment A.1 Manual Approach Resource-Project Bar Chart Spreadsheet View

Resource Allocation Bar Chart																							
Day(s)		1	2	3	4	5				6	7	8	9			10	11	12	13	14			15
October		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Cr_01	15	34	34	34	10	10				47	47	56	56			51	51	51	64	64			64
Cr_02	15	24	24	24	3	3				39	39	65	65			49	49	66	66	63			63
Cr_03	15	14	14	8	8	23				43	43	46	46			9	9	9	57	57			62
Cr_04	14	19	19	29	29	31				31	41	41	40			40	40	38	38	38			
Cr_05	15	2	2	11	11	11				15	22	22	22			50	50	50	61	61			61
Cr_06	15	32	32	7	7	7				17	17	16	16			44	44	33	33	72			72
Cr_07	14	5	5	18	18	35				35	45	45	75			75	75	54	54	54			
Cr_08	15	1	1	6	6	26				26	26	48	48			55	55	55	67	67			67

Table 5: Assignment A.2 Manual Approach Resource-Project Bar Chart Spreadsheet View (Note Delayed Activities are indicated by Red Borders)

Resource Allocation Bar Chart																																					
Day(s)		1	2	3	4	5				6	7	8	9			10	11	12	13	14			15	16	17	18	19			20	21	22	23	24			25
October		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6
Cr_01	15	34	34	34	10	10				47	47	56	56			51	51	51	64	64			64	71	79	79	81			69	69	30	30	13			13
Cr_02	15	24	24	24	3	3				39	39	65	65			49	49	66	66	63			63	70	70	83	76			76	76	36	36	12			12
Cr_03	15	14	14	8	8	23				43	43	46	46			9	9	9	57	57			62	80	80	80	68			68	4	4	4	52			52
Cr_04	14	19	19	29	29	31				31	41	41	40			40	40	38	38	38				78	78	78	74			74	42	42	42				
Cr_05	15	2	2	11	11	11				15	22	22	22			50	50	50	61	61			61	77	82	82	82			37	37	25	25	25			
Cr_06	15	32	32	7	7	7				17	17	16	16			44	44	33	33	72			72	20	20	84	84			28	28	28	58	58			
Cr_07	14	5	5	18	18	35				35	45	45	75			75	75	54	54	54				59	85	85	85			27	27	73	73	73			
Cr_08	15	1	1	6	6	26				26	26	48	48			55	55	55	67	67			67	60	60	21	21			21	53	53	53				

Table 6: Assignment A.3 Manual Approach with Emergency Project Resource-Project Bar Chart Spreadsheet View (Note Delayed Activities are indicated by Red Borders)

Resource Allocation Bar Chart																																					
Day(s)		1	2	3	4	5				6	7	8	9			10	11	12	13	14			15	16	17	18	19			20	21	22	23	24			25
October		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6
Cr_01	15	34	34	34	10	10				47	47	56	56			51	51	51	64	64			64	71	79	79	81			69	69	30	30	13			13
Cr_02	15	24	24	24	3	3				39	39	65	65			49	49	66	66	63			63	70	70	83	76			76	76	36	36	12			12
Cr_03	15	14	14	8	8	23				43	43	46	46			9	9	9	57	57			62	80	80	80	68			68	4	4	4	52			52
Cr_04	14	19	19	29	29	31				31	41	41	40			40	40	38	38	38				78	78	78	74			74	42	42	42	84			84
Cr_05	15	2	2	11	11	11				15	22	22	22			50	50	50	61	61			61	77	82	82	82			37	37	25	25	25			
Cr_06	15	32	32	7	7	7				E	E	17	17			44	44	33	33	72			72	16	16	20	20			28	28	28	58	58			
Cr_07	14	5	5	18	18	35				35	54	54	75			75	75	54	54	54				59	85	85	85			27	27	73	73	73			
Cr_08	15	1	1	6	6	26				26	26	48	48			55	55	55	67	67			67	60	60	21	21			21	53	53	53				

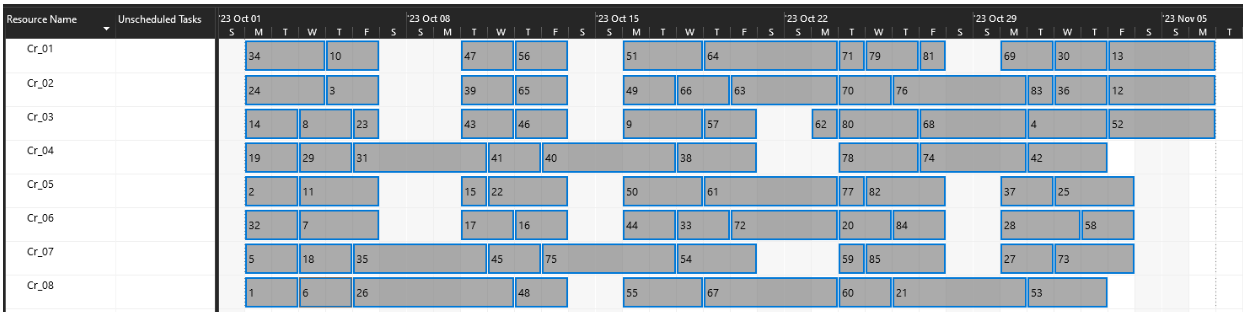

Figure 3. Assignment A.1 and A.2 Manual Approach Resource-Project Bar Chart Microsoft Project View

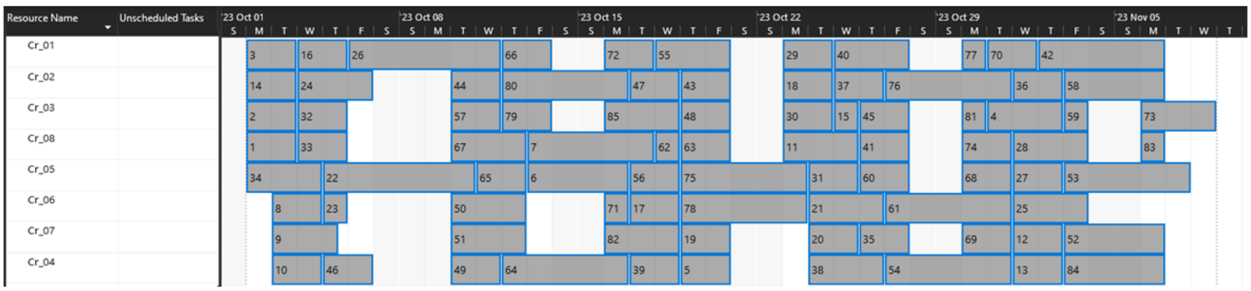

Figure 4. Assignment A.1 and A.2 Microsoft Project Approach Resource-Project Bar Chart Microsoft Project View

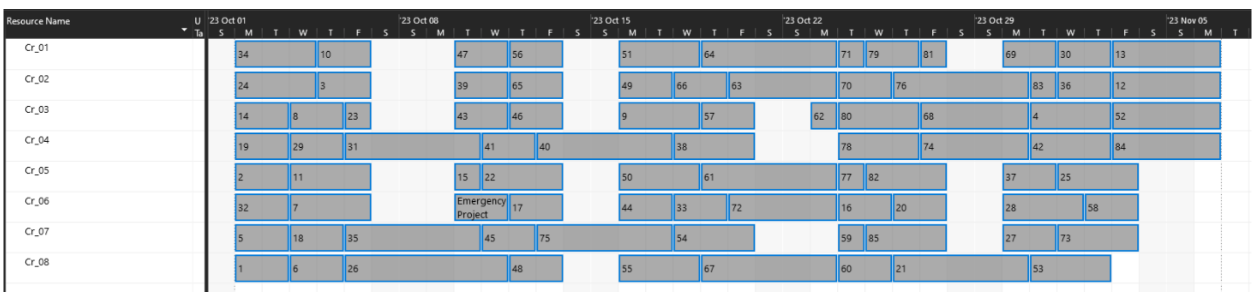

Figure 5. Assignment A.3 Manual Approach Resource-Project Bar Chart Microsoft Project View

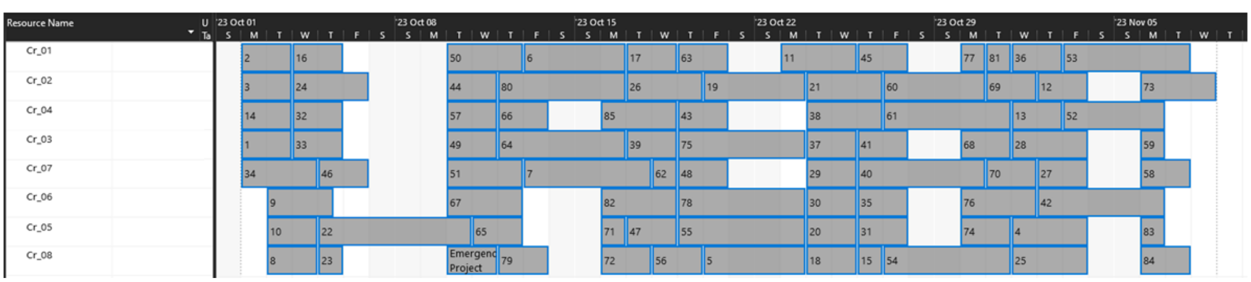

Figure 6. Assignment A.3 Microsoft Project Approach Resource-Project Bar Chart Microsoft Project View

Per the manual RCMPSP solution for A.1, a total of 50 projects are scheduled between October 2 and 23. A total of 17, 21, and 12 priority 1, 2, and 3 projects, respectively, are planned, though no priority 4 and 5 projects are scheduled to maximize execution of higher priority projects.

Regarding A.2, all projects are scheduled by November 6, 9 days past the target October 28 portfolio completion date, with 62 projects completed before the deadline date, and 23 projects delayed. Furthermore, for A.3, with the addition of the emergency project, 24 projects are now delayed past the deadline date, with 61 original projects and the emergency project scheduled on-time. The overall portfolio end date of November 6 remains unchanged. This result aligns with the approach in which resources are reallocated from a lower priority project to complete the emergency project.

Alternatively, using Microsoft Project, a portfolio completion date of November 8 is required to implement all 85 projects. A total of 44 projects are executed prior to the completion date and 41 projects are delayed. Adding in the emergency project results in a delay of 42 projects with 43 projects and the emergency project scheduled on-time. The addition of the emergency project also does not change the portfolio completion date. These observations comparing schedules for both methodologies are summarized in the following figures.

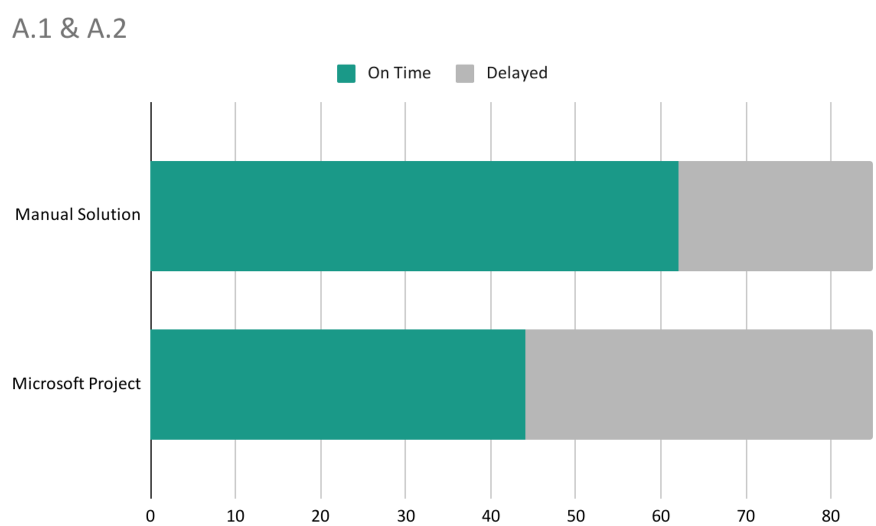

Figure 7. Assignment A.1 and A.2 Manual and Microsoft Project Approach Comparison Summary

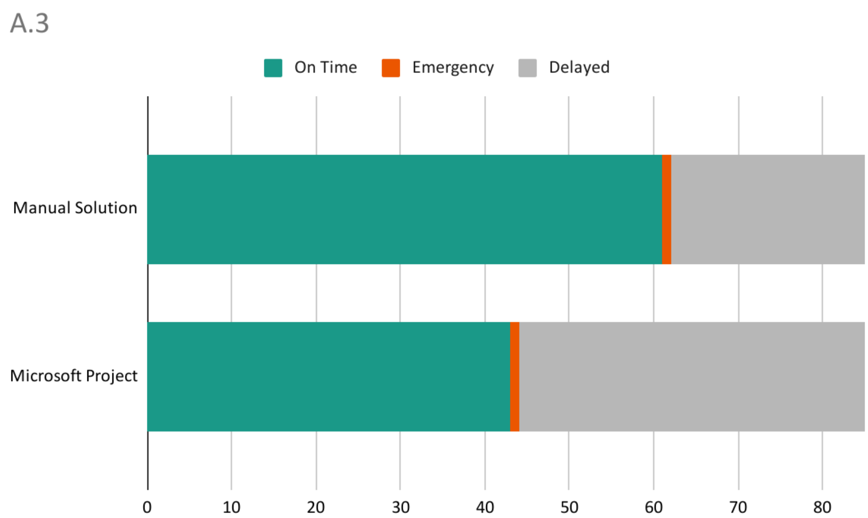

Figure 4. Assignment A.3 Manual and Microsoft Project Approach Comparison Summary

Compared to the manual solution, the Microsoft Project approach exhibits more gaps between scheduled projects and requires an additional 2 days to complete all projects per A.2. The manual solution also accommodates timely implementation of 18 more projects compared to the Microsoft Project schedule. Moreover, the manual solution causes an additional delay of 1 project from the original A.2 baselined schedule, whereas the Microsoft Project plan results in 2 more projects being unable to meet their target end date.

As such, these results indicate the manual approach enables generation of a schedule that is better able to meet the project objectives compared to the Microsoft Project solution. This is particularly evident in the manual solution's ability to minimize execution timelines, while maximizing the number of higher priority projects incorporated in the planning horizon. Furthermore, the manual planning methodology allows for schedule robustness during the addition of a new project by minimizing adjustment to the baseline schedule. This is reasonable as Microsoft Project's scheduling software takes project priority as its primary means of prioritization, whereas Group 7's manual solution involves considerations of multiple factors, namely prioritization, slack, and specified project dates, allowing for optimization of project scheduling to minimize non-productive time.

4.2 Assignment B

The results of the RCMPSP solution are shown in the resource-project interaction table below:

Table 7: Assignment B Resource-Project Bar Chart

Days	Capacity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Cr_01	15	**9**	**9**	**10**	**10**	**13**			**13**	**6**	**6**	**7**	**7**			**15**	**15**	**16**	**16**	**16**		
Cr_02	14	**18**	**18**	**20**	**20**	**3**			**3**	**17**	**17**	**11**	**11**			**11**	**19**	**19**	**19**			
Cr_03	15	**4**	**4**	**4**	**8**	**8**			**8**	**12**	**12**	**12**	**12**			**2**	**2**	**2**	**2**	**2**		
	Delay																					
	Unplanned	1	5	14																		

The scheduling exercise, as displayed above, fully maximizes resource capacity and notably concentrates instances of delay. Delayed activities are identified in blue, while weekends, where no work occurs, are highlighted in black. A minimal number of projects remain unplanned, specifically Projects #1, #5, and #14. Under this scheduling framework, it is projected that the contractor would realize earnings of $148,450.00 for completed projects (determined by subtracting total delay costs and LDs from the total contract price), with $56,550.00 incurred in delay penalties including LDs, in comparison to the total contract price of $205,000.00 across all projects.

5 CONCLUSION

This report has thoroughly explored the complexities and methodologies necessary for scheduling multiple resource-constrained projects, with a specific focus on municipal drainage and water infrastructure projects, in addition to projects with commercial, business, or education relevance. As illustrated in Assignments A and B, a key consideration in project planning are varying project priorities and mitigation of financial impacts, given the contractual clauses allowing clients to claim damages or terminate contracts when delays exceed agreed-upon limits.

Two approaches for project planning are considered in Assignment A. Group 7 employed the manual approach in which project priority, minimum slack, start, and completion dates are contemplated to prioritize projects for resource allocation. As validation, Microsoft Project is utilized to provide an alternative schedule for results comparison, where project priorities form the basis of scheduling priority.

Using the manual method, 17, 21, and 12 priority 1, 2, and 3 projects, respectively, are incorporated in the schedule between October 2 and 23, for a total of 50 projects planned in A.1. Scheduling all projects yielded an overall completion date of November 6, with 62 projects completed on-time. To prioritize completion of the emergency project on October 10, 1 additional project in the baseline schedule was delayed, though overall portfolio timelines remain uncahnged.

Planning all 85 projects via Microsoft Project provides a completion date of November 8, 2 days later than the manual method, with 18 more projects unable to meet implementation deadlines. Two more projects per the A.2 baseline schedule experience delays past execution timelines to facilitate prompt completion of the emergency project.

These results indicate the manual approach provides an optimal scheduling solution to the RCMPSP by reducing overall portfolio timeline, limiting the number of delayed projects, and minimizing non-productive time in the plan. Through contemplation of various scheduling factors outlined in RCMPSP solutions described in available literature, the manual methodology also provides the benefit of reducing impacts to the baseline plan when faced with new project arrival.

In Assignment B, the resource slack-based priority rule proposed by Lawrence and Morton (Lawrence and Morton 1993), is employed due to its effectiveness in reducing the costs of project delays and facilitating effective use of available resources. Group 7 modified the priority index calculation proposed to incorporate LDs into the formula. While this is a novel approach that has yet to be explored in literature, combining LDs and daily penalties allows for a comprehensive consideration of total project delay costs during the scheduling exercise.

The outcomes of the Assignment B scheduling strategy are demonstrably successful. The optimization of crew resource utilization, coupled with a concentrated effort to minimize delay occurrences, indicates the effectiveness of the prioritization and scheduling approach. The minimal number of unplanned projects, specifically Projects #1, #5, and #14, further reinforces the advantages of this methodology. Moreover, the forecasted earnings for the contractor, standing at $148,450.00 against a total contract price of $205,000.00 across all projects, emphasize the financial benefits of implementing the proposed approach.

In summary, the implementation of scientifically supported, priority-based scheduling systems with distinct resource allocation characteristics, and in the case of Assignment B, integrated with considerations for delay penalties, has provided a robust solution to the problem posed in the term project. These strategies not only offer a practical blueprint for the current case studies but also establishes a model for similar project management scenarios in the future.

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APPENDIX A: Matlab Code Utilized in the Assignment B Methodology

```
clc

clear all

%% Parameters configuration

ID=[];% project ID

for i=1:20

    ID=[ID i];

end

ID_mapped=[];% scheduled project

% ID_mapped=[9 10 13 6 7 15 16 18 20 3 17 11 19 4 8 12 2];

% ID_mapped=[9 10 13 6 7 15 16 18 20 3 17 11 19 4 8];

t=1;% date currently being scheduled

p=[4 5 2 3 4 2 2 3 2 2 3 4 2 3 2 3 2 2 3 2];% duration

p_bar=mean(p);% average duration

w=[1000 1050 750 1000 900 800 800 950 900 900 950 1100 900 900 900
1000 850 950 1000 950];% the penalty costs incurred for each time unit
of delay

CP=[10000 15000 9000 10000 12000 10000 10000 11000 10000 10000 11000
12500 10000 10000 8500 9500 8500 9000 10000 9000];% Contract Price

LD=[12500 18750 11250 12500 15000 12500 12500 13750 12500 12500 13750
15625 12500 12500 10625 11875 10625 11250 12500 11250];% Liquidated
Damage

F=LD-CP;% difference between CP and LD

due_date=[10 11 8 9 10 8 8 10 8 8 10 11 8 10 10 11 10 8 10 9];

deadline=[14 15 11 11 12 11 11 14 11 11 13 15 12 12 12 15 13 11 15
11];

l=due_date-p;% the latest starting date for a project before delay
costs are incurred

m=deadline-p;% the latest starting date for a project before
liquidated damage are incurred

k=12;% empirically determined planning parameter

P=zeros(1,20);% Priority

%% Calculation of P_ij
```

```
for i=1:20
    P(i)=w(i)/p(i)*exp(-(l(i)-t)/(k*p_bar))+F(i)/p(i)*exp(-(m(i)-t)/(k*p_bar));
end
%% Priority-based sorting
[sortedMatrix, originalColumnIndices] = sort(P, 2, 'descend');
isNotIn = ~ismember(originalColumnIndices, ID_mapped);
result=originalColumnIndices(isNotIn)
% result=sortedMatrix(isNotIn)
%% Numerical results
sum_CP=sum(CP);% Total Contract Price
Earn=sum(CP)-(10-8)*w(7)-(12-10)*w(15)-(15-11)*w(16)-(12-11)*w(11)-(14-10)*w(19)-(15-11)*w(2)-LD(14)-LD(5)-LD(1);% Total Contract Price substract delay costs and liquidated damage
```