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PLANNING AND SCHEDULING DRAINAGE INFRASTRUCTURE MAINTENANCE OPERATIONS UNDER HARD AND SOFT CONSTRAINTS: A SIMULATION STUDY

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ABSTRACT

The problem of planning drainage services in a certain timeframe by a typical municipal infrastructure maintenance organization lends itself well to existing solutions for resource constrained project scheduling optimization. However, the optimized schedule could be deemed insufficient from a practitioner’s perspective as the very crucial soft constraint on the competence of a particular crew handling different jobs is excluded. We define a crew-job matching index ranging from 0 to 1 to allow for a planner's assessment to be factored in job schedule simulation and optimization. The *total crew-job matching index* (TCJMI) is further defined, accounting for all the crew-job assignments and indicating the fitness of a formulated plan. TCJMI is maximized in the resource-constrained schedule optimization by applying Excel Solver add-in. As such, the planner’s preference and experience can be represented and factored in crew-job scheduling optimization, which is demonstrated through conducting “what-if” simulation scenario analyses.

1 INTRODUCTION

The drainage network is a critical component of the municipal infrastructure that collects sewer and wastewater from residential, industrial, and commercial sources and transfers it to centralized treatment facilities. As the drainage network's performance directly affects the quality of life and the environment, the entire system needs to be maintained at a desirable operational level. Conditions of underground utility systems are subject to deterioration due to aging, excessive demand, misuse, exposure, mismanagement, and neglect (Chughtai and Zayed 2008). The Federation of Canadian Municipalities (FCM) reported that approximately 55% of Canada's sewer infrastructure did not meet current standards (Najafi and Kandivali 2005). Therefore, the burden on Canadian municipalities to maintain the drainage networks' operations is continuously on the rise. In reality, implementing a proactive maintenance program remains a challenge due to technological limitations, finite crew resources, and limited budget allocation. In the meantime, as the rehabilitation work is generally performed only when a major failure occurs, it is equally essential for a municipal infrastructure operator to develop an effective risk management strategy (Haas et al. 1995; Wirahadikusumah et al. 1998). Jobs planned for any drainage service crews usually have tightly constrained deadlines, with each job being one of a kind and job locations decentralized over the wide city area (Zaman et al. 2017). Figure 1 displays the spatial distribution of all the jobs handled by a drainage network maintenance service company for over one year in Edmonton, Canada.

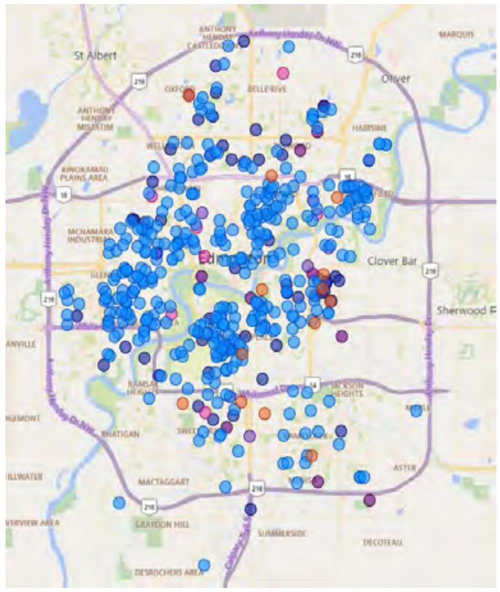


Figure 1: Spatial distribution of all the jobs handled by a drainage maintenance company over one year in the city of Edmonton, Canada.

Job planning and crew use scheduling are subject to distinctive sets of hard and soft constraints. In this application context, hard constraints refer to the job duration, the crew's availability prior to executing a job, the imposed completion deadline on specific jobs, and other time-sensitive approvals of permits. Soft constraints can be a particular crew's competence in handling a specific type of job including (1) knowledge about the situation of a particular neighborhood, (2) experience with operating a particular type of equipment or procedure, and (3) the crew's capability to foresee potential hidden issues and risks before they are manifested in the field. As multiple crews can be the candidate for executing a particular job, the planner needs to avoid overworking some crews and underworking others by well balancing the workload among different crews. Meanwhile, the planner intends to grow the competence of a certain crew in working on a specific type of job and thus allocating such jobs to the crew with higher priority.

In construction, skilled labor resources play a critical role, while their availability is limited and varies from time to time (Haplin et al. 2017). At the work planning stage, the decision on resource provisions (including the number of self-employed crews and the quantity of subcontractors if needed) is largely made based on experiences of project managers and schedulers. The problem of allocating a limited quantity of crews to execute a given set of jobs with time constraints is generally classified as the problem of resource constrained project scheduling (Hegazy and Menesi 2012). Each job has a definitive scope, location, type, duration, and resource requirements; some jobs can be subject to completion deadlines. Existing resource scheduling optimization techniques can be applied to assign crews to each job in search of the shortest total project time while meeting all the hard constraints such as job deadlines and limited crews. Adding the very crucial soft constraint of crew competence at handling different jobs would extend the current resource-constrained scheduling problem. Nonetheless, the major research challenge is how to represent a planner's preference and experience in crew-job scheduling optimization. In this research, we define a crew-job matching index (CJMI) ranging from 0 to 1, which allows for the experienced planner's assessment of crew competence to be factored in job schedule simulation and optimization. Besides, the total crew-job matching index (TCJMI) is defined, accounting for all the crew-job assignments and indicating the fitness of the obtained plan. Further, TCJMI is maximized in the resource-constrained schedule optimization by applying Excel Solver. Herein, the optimization objective is to identify the best overall matching between crews and jobs according to crew-job competence assessment by an experienced planner.

This paper also illuminates why the identified problem does not lend itself well to existing solutions in a case study using the *Simplified Scheduling Simulation system (S3)* developed by Lu et al. (2008) based on the simplified discrete-event simulation approach (SDESA) (Lu 2003). *S3* takes advantage of Particle Swarm Optimization (Eberhart and Kennedy 1995) for automating the search of a resource-constrained schedule with the shortest total project duration. Further, using the same case, a new approach of incorporating the subjective crew competence assessment in crew-job planning and scheduling is proposed and prototyped in Excel. The Excel optimization add-in (Solver) is utilized in search of the maximum value of TCJMI. The influence of the soft constraint upon the resulting crew use plans and job schedules is demonstrated in "what-if" simulation scenarios.

2 LITERATURE REVIEW AND PROBLEM DEFINITION

The purpose of developing a construction schedule is to direct resources to deliver the project in a coordinated and timely fashion subject to the limited time and funding available (Halpin et al. 2017). Theoretical foundations and systematic solutions have been developed for addressing implicit resource-constrained precedence relationships in connection with the critical path method (CPM). Optimization techniques have also been applied to optimize resource allocation and keep the extension of the project duration to a minimum or find the lowest project cost (Hegazy 1999; Siu et al. 2017). Rashedi and Hegazy (2015) proposed optimization models using an advanced modeling tool (GAMS/CPLEX) to solve the capital project renewal problem and compares results with genetic algorithms; both solutions proved to be beneficial, yet the advanced mathematical model showed superior performance. Siu et al. (2017) defined a crew job allocation and schedule optimization problem in connection with snow removal operations; the resulting optimization framework encompassed (1) analysis of snow plowing and sanding (or salting) time with consideration of field and managerial constraints, (2) optimization of snow plowing and sanding time based on the modified Floyd-Warshall algorithm, and (3) optimizing shop-road assignments in terms of plowing and sanding operation efforts. Yi and Lu (2018) proposed a fleet optimization solution for earthwork projects using discrete event simulation, revealing the impact of employing different combinations of excavators and trucks upon completing earth-moving jobs. Biruk et al. (2019) proposed a mixed integer binary-based optimization solution for preparing a project schedule based on the subcontractor’s bid value and availability. Lam and Lu (2008) also described a simulation-based approach to assist subcontractors in scheduling limited bar-bending crews to handle jobs over multiple concurring sites, resulting in optimized crew use efficiency along with a substantial reduction of the total duration.

Decision variables and rules for job planning and resource allocation are dynamic in nature and involve implicit factors that cannot be analytically represented and measured (Zhang and Tam 2003). In our case study, crew-job matching, and job scheduling based on the criteria of minimizing total time duration can lead to the assignment of a job to a crew which has limited prior experience with similar jobs. On the other hand, assigning a high priority to a more competent crew in job planning may lead to increased idling time for the other crews and prolonged total project duration. Nevertheless, research has yet to incorporate the subjective assessment of crew performance in job assignment and resource allocation. For instance, the construction planner intends to allocate a particular job to the crew deemed more competent at performing the job. The resultant work plan and job schedule would satisfy both soft and hard constraints, potentially delivering more relevant and effective decision support to the planner. Based on the current practice of drainage network repair and maintenance planning, the defined problem involves the scheduling of n jobs that need to be completed within a specific window of time t with limited m number of available crews. If crew resources are proven to be insufficient, engaging extra crews (external contractors) would be justified. Herein, one crew can be allocated to one job at a time; there is no technology-constrained precedence relationship among multiple jobs distributed across the city. Each job represents a unique instance of a particular type of work that requires a crew for a certain time duration (days), and any available crews are capable of handling any of the unassigned jobs. It is noteworthy that from the perspective of the experienced planner, crew performance varies in processing different types of work, which means a particular crew is assessed at different competence levels given a different type of work. The optimized job schedule is intended to shorten total project duration and optimize the crew-job matching, aiming to achieve the highest overall crew competence and balanced utilization among all the available crews.

Multiskilling is a popular workforce strategy that reduces indirect labor costs, improves productivity, and reduces turnover. A multiskilled workforce is one in which the workers possess a range of skills that allow them to participate in more than one work process (Gomar et al. 2002). It is noteworthy that despite certain similarities, the job crew assignment problem being addressed differs markedly from the multiskilled labor scheduling problem. Herein, a crew consists of a mix of specially trained employees and equipment; a crew is assigned to one job as a collective resource that will not be assigned to another one until the job is finished. One crew can be assigned to different jobs performing at various levels of competency (as indicated by CJMI). Hence, it is not necessary to explicitly define the trade skills of individual crew members and factor in productivity variations due to employing multiskilled trades.

3 ILLUSTRATING CASE

The work planning scenario typical of a drainage services provider is defined in this illustrating case. In general, the distributed service request is logged in a central system. A list of jobs, each demanding the engagement of a crew for a short period of time (two to three days), is compiled and then handed over to the service operation manager, responsible for assigning available crews to each job scheduling all the jobs. In this case, there are a total of 13 jobs, as shown in Table 1. It is assumed that those jobs have been recorded over the last three days and need to be scheduled to deploy available crews starting from the next morning. There are a total of six crews available for handling all the jobs.

Table 1: List of jobs that are ready for scheduling.

Job ID	**Task**	**Duration**
Job 1	Replace Catch Basin Barrel	5
Job 2	Reline Storm Service Line	4
Job 3	Repair Storm Service Line	3
Job 4	Reinstate Catch Basin Lead	2
Job 5	Repair Culvert	3
Job 6	Reline Storm Services	3
Job 7	Replace Storm Service Line	4
Job 8	Reinstate Catch Basin Lead	2
Job 9	Repair Culvert	2
Job 10	Place RIP RAP	5
Job 11	Patch Catch Basin Hole	3
Job 12	Partial Storm Line Repair	3
Job 13	Patch Catch Basin Hole	4

3.1 Scenario 1: Optimization for Least Total Duration

This case falls in the classical resource-constrained optimization problem. In the base case scenario, we used "*S3*" to identify the optimum solution with the least total duration, and the results are shown in Figure 2. The total minimum time required to complete all thirteen jobs is nine days. The crew work schedule as per *S3* simulation is also shown in Figure 3.

Job ID	Task	Duration	Start Time	Finish Time
Job 1	Replace Catch Basin Barrel	5	0	5
Job 2	Reline Storm Service Line	4	0	4
Job 3	Repair Storm Service Line	3	0	3
Job 4	Reinstate Catch Basin Lead	2	0	2
Job 5	Repair Culvert	3	0	3
Job 6	Reline Storm Services	3	0	3
Job 7	Replace Storm Service Line	4	0	4
Job 8	Reinstate Catch Basin Lead	2	0	2
Job 9	Repair Culvert	2	0	2
Job 10	Place RIP RAP	5	0	5
Job 11	Patch Catch Basin Hole	3	2	5
Job 12	Partial Storm Line Repair	3	2	5
Job 13	Patch Catch Basin Hole	4	2	6

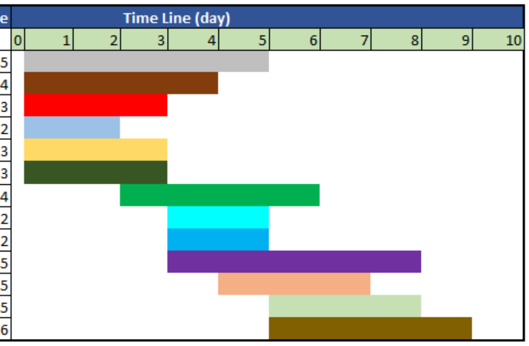


Figure 2: Job schedule for the example case "Scenario 1".

Crew ID	Assigned Jobs
Crew 1	Job 1
Crew 2	Job 2
Crew 3	Job 3
Crew 4	Job 4, Job 11
Crew 5	Job 5
Crew 6	Job 6

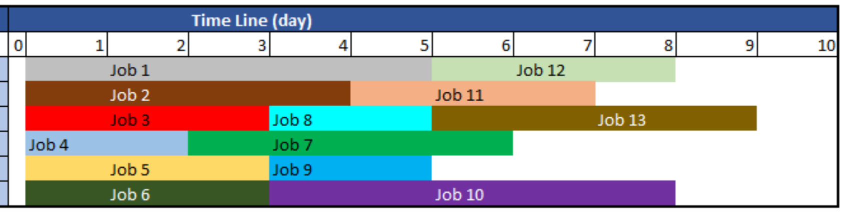


Figure 3: Crew allocation schedule for the example case "Scenario 1".

4 REPRESENTING SOFT CONSTRAINT IN CREW JOB SCHEDULING

Although *S3* produces the optimum solution, it may not provide the proper crew allocation plan that is acceptable by the operations manager in the real world. In an ideal setting, all the available crews are identical, and each one can be assigned to perform at the same competence level in each category of work. However, in practice, considerable variations among crews exist in handling a certain job, which are not straightforward to be represented as constraints in resource scheduling simulation and optimization analysis. For instance, one crew has gained substantial experience in a certain type of work and thus earned "competence" reputation in the planner's mind. In contrast, the other crew may have demonstrated less comprehensive comprehension of the scope and the difficulty in conducting similar jobs in the past. One crew could have demonstrated a better familiarity with the neighborhood of a particular job and developed trust with the main stakeholders than others. Some crews work better on jobs under the tight deadline constraint, while others perform better on jobs with more flexibility and time floats. Some crews have taken the most updated safety training in operating specialized equipment, while the other crew has yet to do so.

When assigning a crew to each job, the operation planner subconsciously assigns a score in matching each crew with the given job and then selects the top scorer for the job. Moreover, the planner needs to avoid underworking or overworking crews (i.e., one crew has no or too light job assignment in the next week, where the other crew has to work overtime). Therefore, one objective of the operations planner is to devise a solution where all available crews are utilized in a balanced manner, and at the same time, crews are matched with jobs as per the planner's perception to the maximum degree. The resulting job schedule solution needs to satisfy both hard scheduling constraints and soft planning constraints.

The following section introduces the definition of CJMI (crew-job matching index), which is proposed to effectively incorporate the soft constraint in crew use planning and project scheduling in the present case study.

4.1 Crew-Job Matching Index (CJMI)

In reality, planners largely rely on their own experience and gut feelings, with the support of limited historical job records. In most cases, historical records can be unavailable, incomplete, irrelevant, or inconsistent, potentially causing more confusion. Hence, subjective judgment by domain experts with relevant knowledge and experience provides the practical means to formulate such a competency score for each crew (Paek et al. 1993). The fuzzy set, formalized by Zadeh (1965), is found to be most appropriate to apply in such a case where a rational approach toward decision-making should take into account human subjectivity, as opposed to only employing objective probability measures (Kahraman et al. 2006).

A set of pseudo fuzzy scores denoting crew performance for each job type is given in Table 2 (crew job matching index table). These scores are termed, the "*crew-job matching index (CJMI)*" formulated based on subjective assessment of a particular crew's performance on a specific job. As discussed in the earlier section, each crew is capable and qualified to handle all the job types; but the planner has formed an opinion, judgment, preference for crew-job matching over years of experience reflecting on numerous factors that cannot be explicitly defined and analytically evaluated (such as crew's competence, reputation, motivation). CJMI is actually a fuzzy number with 1 meaning "Perfect match," 0 meaning "To-avoid-if-possible." These scores are supposed to be evaluated and entered by the human planner in the process of allocating a crew to each job. If the *CJMI* score is below 0.50, the planner generally prefers not to assign that crew to that job. In short, a fuzzy number (i.e., *CJMI)* is devised to represent the soft constraint critical to simulating the identified crew-job planning and scheduling problem in the practical application context of maintaining drainage services.

Table 2: Crew job matching index for different jobs.

Job ID	**Type of Work**	**Crew 1**	**Crew 2**	**Crew 3**	**Crew 4**	**Crew 5**	**Crew 6**
Job 1	Replace Catch Basin Barrel	0.9	0.6	0.7	0.9	0.6	0.7
Job2, Job6	Reline Storm Service Line	0.7	0.6	0.3	0.7	0.6	0.3
Job 3	Repair Storm Service Line	0.5	0.2	0.9	0.5	0.84	0.9
Job 4, Job 8	Reinstate Catch Basin Lead	0.5	0.2	0.8	0.5	0.2	0.78
Job 5, Job 9	Repair Culvert	0.8	0.9	0.5	0.8	0.45	0.5
Job 7	Replace Storm Service Line	0.9	0.5	0.2	0.9	0.63	0.2
Job 10	Place RIP RAP	0.56	0.77	0.63	0.56	0.87	0.63
Job 11, Job 13	Partial Storm Line Repair	0.55	0.81	0.63	0.55	0.94	0.49
Job 12	Repair Culvert	0.53	0.84	0.63	0.72	0.74	0.82

4.2 Crew Job Planning Framework

It is emphasized that the planner's objective is to allocate finite crew resources to minimize the total duration, while at the same time ensuring competent crews are matched to all the jobs. The measure of the overall crew competence considering all the assigned jobs can be defined as the "*total crew job matching* *index (TCJMI)*", which is weighted on job duration and factors in the total number of jobs, as given in equation (Eq. 1).

$$TCJMI = \frac{\sum CJMI_{i,j} \times t_j}{\sum t_j} \tag{1}$$

Here, $CJMI_{i,j}$ is the crew-job matching index for crew i, which is assigned to job j, and t_j is the duration of the job j. As per Eq. 1, given all the jobs for Scenario 1 and using the *CJMI* values taken from Table 2 for each crew, the *TCJMI* value is calculated to be 0.618. Although the planner is satisfied with total project duration resulting from Scenario 1 by applying *S3* (9 days), the *TCJMI* has deemed a marginal pass and is expected to be raised to a higher level (say, above 0.75).

The entire crew-job matching planning framework is summarized with a flow chart, as illustrated in Figure 4. First, the planner needs to set the *TCJMI* limit to 1.0. Then, the *CJMI* values are assessed for available crews and jobs. The objective function is to achieve the maximum *TCJMI* score (Eq. 2) subject to crews being assigned to each job (Eq. 3), any job finish deadlines (Eq. 4) or the deadline to finish all the jobs in the job bucket (Eq. 5). Excel Solver is used to find the optimum solution in terms of crew job matching. Next, *S3* is run to find the shortest total duration and generate crew job schedule, ensuring that the number of crews required at any particular time t is always less or equal than the total number of available crews (Eq. 6). In the end, the planner needs to check the total duration and the *TCJMI* of the obtained plan. If the planner is satisfied, the crew job plan will be ready for execution; otherwise, the available crew numbers and job profile definition need to be revised, and CJMI updated accordingly prior to running the analysis on a new scenario.

Solver objective function:

$$\text{Max}\ (TCJMI) \tag{2}$$

Subject to,

$$N(C_t) \leq N(C) \tag{3}$$

$$J_{FN} \leq J_D \tag{4}$$

$$P_{FN} \leq P_D \tag{5}$$

$$N(C_A) \leq N(C_R) \tag{6}$$

Where,
Total number of crews required at any time $t = N(C_t)$;
Total number of crews available = $N(C)$;
Job finish time = J_{FN}; Job deadline = J_D; Project finish time = P_{FN}; Project deadline = P_D;
The number of crews assigned to each Job = $N(C_A)$; Number of crews required by job = $N(C_R)$.

5 CASE STUDY WITH ALTERNATE SCENARIOS

5.1 Scenario 2: Rescheduling Base Case to Enhance TCJMI

Scenario 1 shows the optimum schedule solution, where crew-job competency constraints (i.e., CJMI) are ignored entirely while running S3 simulation and optimization. If the planner wants to increase the *TCJMI* for the obtained plan and, at the same time, wants to keep all the crews engaged, (each crew is assigned with one job at least), an alternative scenario is postulated. A new crew job schedule (Scenario 2) is formulated by running Excel Solver optimization again. Figure 5 shows the updated job completion plan; the corresponding crew allocation plan is given in Figure 6. It is noteworthy the *TCJMI* for this scenario is determined as per Eq. 1 as 0.77 against 0.618 in Scenario 1, despite total time duration increasing from 9 days in Scenario 1 to 12 days.

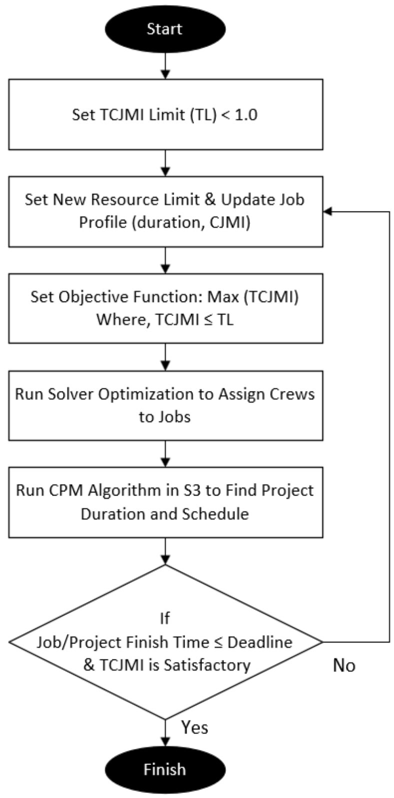
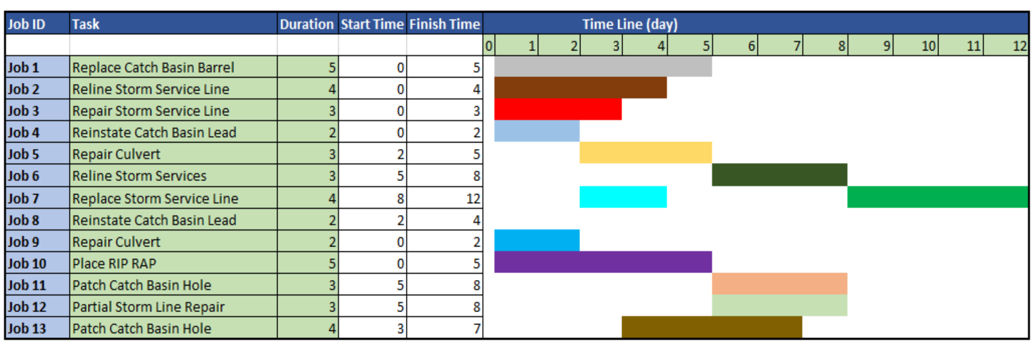
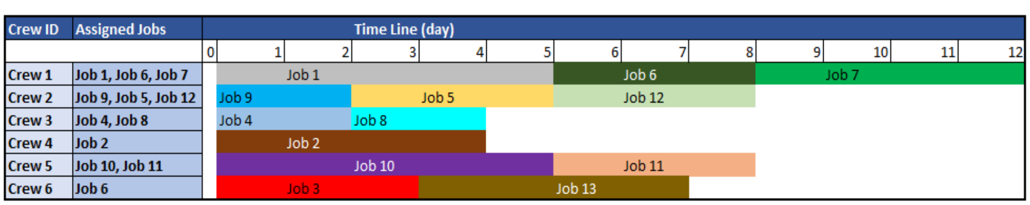


Figure 4: Crew job matching and scheduling framework.



Job ID	Task	Duration	Start Time	Finish Time
Job 1	Replace Catch Basin Barrel	5	0	5
Job 2	Reline Storm Service Line	4	0	4
Job 3	Repair Storm Service Line	3	0	3
Job 4	Reinstate Catch Basin Lead	2	0	2
Job 5	Repair Culvert	3	2	5
Job 6	Reline Storm Services	3	5	8
Job 7	Replace Storm Service Line	4	8	12
Job 8	Reinstate Catch Basin Lead	2	2	4
Job 9	Repair Culvert	2	0	2
Job 10	Place RIP RAP	5	0	5
Job 11	Patch Catch Basin Hole	3	5	8
Job 12	Partial Storm Line Repair	3	5	8
Job 13	Patch Catch Basin Hole	4	3	7

Figure 5: Job schedule for the example case "Scenario 2."



Crew ID	Assigned Jobs
Crew 1	Job 1, Job 6, Job 7
Crew 2	Job 9, Job 5, Job 12
Crew 3	Job 4, Job 8
Crew 4	Job 2
Crew 5	Job 10, Job 11
Crew 6	Job 6

Figure 6: Crew allocation schedule for the example case "Scenario 2."

5.2 Scenario 3: Rescheduling with One Less Crew

The planner can further alter the plan considering that one crew (Crew No. 6) would take a vacation in the near future or be reserved for an upcoming emergency job. Therefore, Crew No. 6 will be unavailable in planning the current job set. The planner can alter the plan again with the same intention to maximize crew job matching while minimizing total project duration. Instead of six crews, only five crews are available in updating the optimization model. The resulting schedule for this scenario and the crew allocation schedule is shown in Figure 7 and Figure 8, respectively.

Note that in contrast with Scenario 2, with one less crew, the calculated *TCJMI* value for the job bucket remains at 0.77, while the total time duration (12 days) remains unchanged. This indicates Crew No. 6 is actually not needed to handle the 13 jobs being planned.

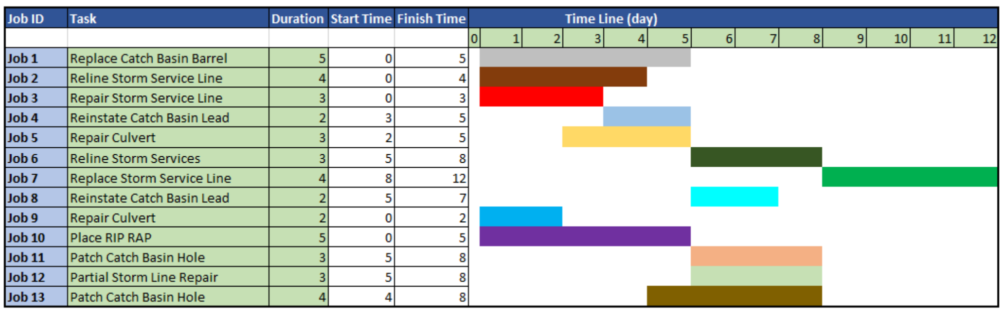


Figure 7: Job schedule for the example case “Scenario 3.”

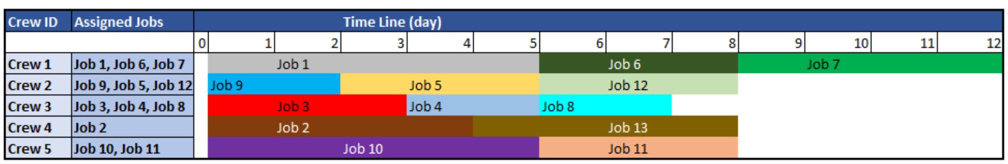


Figure 8: Crew allocation schedule for the example case “Scenario 3.”

5.3 Scenario 4: Rescheduling When One Job is Contracted Out

It is assumed one job is canceled (e.g., a job falls in a different jurisdiction’s boundaries). Thus, six crews are available to be allocated for handling the remainder of 12 jobs. What would happen to the work plan and job schedule in such a new scenario? By keeping all the crews engaged while at the same time maximizing the crew job matching performance, the optimum job schedule (Figure 9) is formulated by using Excel Solver. The resulting crew schedule is shown in Figure 10. Note that the calculated total duration, in this case, reduces to 8 days with a *TCJMI* value of 0.756.

A summary table for contrasting the four “what if” scenarios is presented in Table 3. The planner/operation manager is advised to implement *Scenario 3,* given 13 jobs and employing five crews; alternatively, with one less job, implementing *Scenario 4* deploying six crews on 12 jobs is recommended.

Table 3: Summary of results for different crew job allocation scenario analysis.

Scenario	Total Job Number	Crew Number	Duration (Days)	TCJMI
Scenario 1	13	6	9	0.618
Scenario 2	13	6	12	0.770
Scenario 3	13	5	12	0.770
Scenario 4	12	6	8	0.756

Figure 9: Job schedule for the example case "Scenario 4."

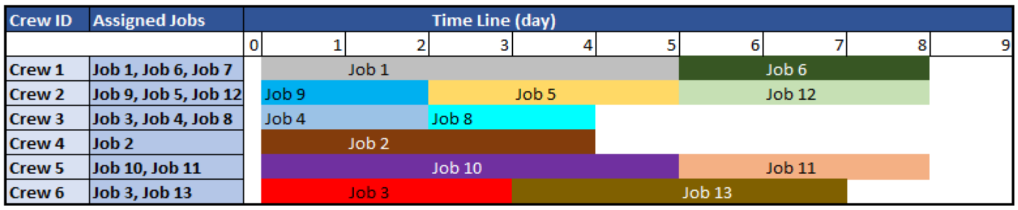


Figure 10: Crew allocation schedule for the example case "Scenario 4."

6 CONCLUSION

As the performance of a drainage network directly affects the quality of life and the environment, the entire system needs to be maintained at the required operational level. This research addresses crew-job matching planning and crew use scheduling in the application context of providing short-term drainage maintenance services by a typical municipal infrastructure maintenance organization. In an ideal setting, all the available crews are identical, and each one can be assigned to perform at the same level in each category of work. However, in practice, considerable variations among crews exist in handling a certain job, which are not straightforward to be represented as constraints in resource scheduling simulation and optimization analysis. Although the optimization engine of the Simplified Scheduling Simulation (S3) produces an optimum solution, it does not provide the proper crew allocation plan that is acceptable by the operations manager in that the simulation does not factor in the variation in perceived competence levels for a specific crew in handling different jobs. When assigning a crew to each job, the operation planner subconsciously assigns a score in matching each crew with the given job and then selects the top scorer for the job. The crew-job matching index has been specifically proposed to incorporate the soft constraint as defined in the crew use planning and project scheduling. As demonstrated through conducting "what-if" simulation scenario analyses on a case study, the proposed method sufficiently simulates the decision process of the experienced operation planner and produces optimum job schedule solutions that satisfy both hard and soft constraints in this real-world crew job planning and scheduling problem.

In the present research, the "*crew-job matching index (CJMI)*" denotes a set of pseudo fuzzy scores implying crew performance for each job type, which is based on subjective assessment of a particular crew's performance on a particular job by an experienced practitioner. In the near future, a less subjective, consistent assessment of CJMI by using effective AI, experts' know-how, and historical data will be pursued. Classifying jobs and estimating job duration will also be enhanced using operations data and AI modeling to feed the Excel optimization program. On the other hand, the research methodology and the Excel prototype program will also be improved in terms of accounting for crew workload balance and updating "to complete" job duration with actual feedback on crew job completion in rolling the plan to the next period.

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