DRONE ROUTING FOR DAMAGE ASSESSMENT ON POWER DISTRIBUTION SYSTEMS UNDER HILF EVENTS

by

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ABSTRACT

MAHESH ALAPATI. Drone routing for damage assessment on power distribution systems under HILF events (Under the direction of Dr. CHURLZU LIM)

Significant damages caused by extreme weather conditions such as flood, storm, hurricanes, blizzards etc., contribute multiple and widely-spread damages to electric power transmission and distribution systems resulting in large-scale power failures. In such cases, the electric utilities send repair crew to affected locations as soon as possible to repair the transmission and distribution systems. Damage assessment process is one of the steps in system restoration process, which assesses overall damage and gives out an approximate restoration time for the damaged location. Until now, a team of technicians manually did damage assessment process by inspecting every affected location. In this thesis, a systematic method of the damage assessment procedure is proposed in an effort to reduce the restoration time in conjunction with drone technology. In the past, damage assessors have inspected locations under various hazardous events circumstances like heavy rain and wind, and sometimes paths to damaged areas are inaccessible due to disruption caused by the HILF events. Drone technology offers good potential to make the restoration process more efficient and safe. This thesis, proposes a drone routing algorithm that provides a drone path covering the entire part of damaged area of a circuit. It is also proposed how to integrate the algorithm into the overall restoration process. Detailed procedure is illustrated on a real distribution network as a case study.

ACKNOWLEDGEMENTS

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CHAPTER :1 INTRODUCTION

High impact low frequency (HILF) events such as hurricanes, ice storms, blizzards, and high-speed winds cause heavy damage to electrical transmission and distribution grid. For example, Hurricane Irma damaged the entire power system of the U.S. Virgin Islands in September 2017, which resulted in 20,000 residents to stay without power [1]. In addition, Hurricane Maria in October 2017 devastated Puerto Rico's electrical system into pieces. Duke Energy workers have been working to restore power in Puerto Rico since January 2018 [2].

Figure 1: Trees and power lines downed by Hurricane Maria in 2017 [3]

When there is no power, people suffer from absence of various resources. So, it is very crucial to restore the power distribution system as soon as possible to regain power to all customers.

Restoration of electrical services after HILF events is a multiple step process with different personnel and resources deployed. The restoration procedure can be divided into three sequential phases: 1) before the storm, 2) during the storm, and 3) after the storm. Each phase has different tasks to accomplish as described in the following [4].

In the before the storm phase, weather forecasts are collected from various prediction models. When utilities foresee any potential damage to the grid from the forecasts, they prepare for the storm with material procurement and staffing crew members. Sometimes utilities ask for support from neighboring utilities if they do not have enough resources to cope with severe expected damage.

During the storm, a utility coordinator looks at resources and decides on the roles of internal and external crews. Most restoration crews remain on standby while only emergency restoration is performed such as hospitals, and prisons. Outage reports are accumulated and documented in this phase.

After the storm, the first step of the restoration process is to assess damages and estimate the amount of material and crew resources needed to restore power to customers. A damage assessor is deployed to the part of a circuit (or the entire circuit), where outage has occurred, to inspect the distribution lines. As damages are being assessed, damage information is transmitted to the coordinator, who dispatches available restoration crews and assign materials.

Recently, unmanned aerial vehicles have been used in energy industry to inspect solar panels, wind turbines, transmission lines and other structures. For example, Duke Energy uses drones with a thermal imaging device that identifies faults in solar panels. In addition to solar plants, they use drones to assess storm damage, to inspect towering equipment, and to track construction from beginning to end. Duke Energy was one of the first operators in the United States to use drone technology in power restoration by using drones in Puerto Rico after Hurricane Maria in October 2017 [5]. Drones help crewmembers find damages such as broken poles, downed power lines in densely vegetated areas, and to uncover safe paths for crew members in hazardous areas.

Figure 2: Drone inspection in mountain peaks in Puerto Rico [6]

Figure 3: Drone over power lines controlled by pilot [6]

It is evident that drones can help utilities reduce operation cost, provide useful information about affected area through video surveillance, and more importantly furnish safety to workers during hazardous events.

Observing the potential benefit of utilizing drone technology in the context of a power restoration process, we study a systematic damage assessment operation by proposing a drone routing algorithm that provides a drone path covering the entire part of the circuit under consideration. If the drone routing algorithm is effectively integrated in a damage assessment process, it is expected to make restoration process much faster and efficient.

The thesis is organized as follows. Chapter 2 provides a literature review on the studies about power system restoration process after HILF events and areas relevant to the proposed method. Chapter 3 describes the details of the drone routing algorithm. Chapter 4 presents a case study implements the drone routing algorithm on a real feeder network. Chapter 5 provides a damage assessment process that integrates the drone routing with routing damage assessment units. The conclusion and future work of the research is given in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

In this chapter, we start with a review on studies that consider the system restoration for a power distribution systems. Note that the drone routing problem in this study seeks for a shortest (or minimal) path to inspect a given part of a distribution network that experiences power outage. This problem is closely related to Chinese Postman Problem (CPP) [7], and its generalization, Rural Postman Problem (RPP) [8]. Essentially, the proposed procedure provides a solution of CPP for a network augmented from the power distribution network. Accordingly, reviews on the CPP and RPP are also provided. The proposed procedure also has a step that requires a solution to a matching problem. Hence, a review on the matching problem is also provided in what follows.

2.1 Review on Power Distribution System Restoration Process

Restoration of electrical services is a multiple step process for a utility to restore the power as quick as possible when a HILF event occurs. Considering post-earthquake electric power restoration tasks, Xu et al. [9] propose a stochastic integer program, which minimizes the average time of customer without power. Their model determines how to schedule inspection, damage assessment, and repair tasks in the post-earthquake restoration of the electric power system. In the initial phase, operators inspect the generation stations and substations, while priority is given to substations that are closer to the epicenter of the earthquake. In the second phase, Damage Assessment Teams (DATs) are dispatched to damaged substations. In the third phase, repair teams are dispatched from operation centers to the damaged substations that have been assessed by DATs. The effectiveness of the schedules generated by solving their optimization model is evaluated via a discrete event simulation study of the restoration process, and is compared with that of the schedules practiced by the power company. They used three measures for comparison: average time without power, time required to restore 90% of customers, and time required to restore 98% of customers. Strategies like restoration time for the first customers and outage duration for the last customers are more effective than current restoration process. This model is applied to the Los Angeles Department of Water and Power electric power system. Liu at al. [10] propose accelerated failure time (AFT) models to estimate the duration of each electric power outage after a storm. The proposed model is a type of survival analysis model, which is built using a dataset about six hurricanes and eight ice storms. AFT models predict the duration of possible outage, and by aggregating estimated outage durations and accounting for variable outage start times, restoration times are estimated. The proposed technique can be applied as storm approaches, before damage assessment process begins, which helps utility inform expected power restoration time to affected customers. This model was applied to hurricane and ice storm events for three major electric power companies on the East Coast of United States. The key limitation of this approach is data availability, by the nature of HILF events.

Neteghi [11] compares the accuracy of predicted power outage duration of five distinct statistical methods. Analysis is based on a dataset containing power outage durations caused by Hurricane Ivan in 2004. Two survival analysis models together with three data mining techniques were implemented to compare the predictive accuracy. These methods are AFT regression, Cox proportional hazard (CPH) regression, classification and regression trees (CART), multivariate adaptive regression splines (MARS), and Bayesian additive regression trees (BART). Through different validation tests, they conclude that the BART-based forecast model offers the most accurate estimates of power outage durations.

Nateghi et al. [12] propose a predictive model, using the method of random forests to forecast duration of power outage prior to hurricane landfall. They attribute long power outage durations to the climatic and geographic characteristics of the service area. The results indicate that the proposed random forecast model predicts outage restoration times with an improved accuracy over existing models. For example, the model is 87 % more accurate than the BART model used by Nateghi [12] on basis of Mean Absolute Error. Kozin and Zhou [13] proposed a model for a lifeline-restoration process after earthquake, based on a discrete-state, discrete-time Markov process. In this lifeline system electricity, water, transportation, railway, and telephone services are considered. The basic principle behind the proposed model is to assign limited resources to different lifelines and minimize total loss, which is caused by damaged lifeline systems. The formulation of damage restoration process of lifeline systems considers two factors 1) initial damage probability state and 2) economic return. To optimize the limited resources that maximize the economic return from lifeline functioning, dynamic programming is used. Nojima and Kameda [14] proposed a procedure to maximize efficiency of overall restoration process using the graph theory and optimization theory. In this paper, the restoration of lifeline network systems is executed in two stages: the first stage extracts tree structures from the network and the second stage determines the repair sequence of damaged network in the tree structure. Horn's algorithm [15] is used to determine the optimal repair sequence. Three types of tree structures such as minimum spanning tree, shortest path tree, and approximately optimum tree are used to find better connectivity of network. Among these minimum spanning trees are found to be the most efficient tree structure in a majority of cases.

Noda [16] proposes a method that uses a neural network to minimize the likelihood of functional loss to a telephone system. The neural network provides a repair sequencing of damaged facilities to determine restoration process. Wang et al. [17] propose a depot location model that efficiently manages the resources that are needed for restoration. The problem is addressed in two phases: (1) minimize total transportation cost – how to locate repair depots and transport required resources from each depot to damaged locations, and (2) determine how additional repair depots would help to minimize total cost (restoration time). Wu et al. [18] propose a fuzzy based approach to present a repair schedule of crew and vehicle routing during various kinds of outages. Their model determines repair priorities of crews and vehicles for effective dispatch to damaged locations. The model is implemented in the Taiwan-power company through of their Outage Management System. Sato and Ichii [19] develop genetic algorithms to perform two tasks (1) to find an optimal restoration order in the damaged network and (2) to allocate resource teams to damaged locations where the objective is to minimize the total restoration time. The proposed model is applied in Japan after 1978 Off Izu-oshima earthquake. Similarly, Sugimoto and Tamura [20] determine which restoration teams should be allocated to damaged sites and optimal order of restoration to minimize the area above restoration curve (equivalently, average time each customer without power).

2.2 Chinese Postman Problem

CPP is a well-known problem that finds a shortest (or least-cost) tour covering all the edges in an undirected (connected) street network. Mei-Ko Kwan, a mathematician at the Shangtun Normal College, considered a problem to address the issue of delivering postal services with minimum possible distance traveled by a postman while covering every street and coming back to the origin where he started [7]. The CPP has many real-world applications such as street sweeping, garbage collection, snow removal, and the inspection of pipes or cables. Summaries of important studies are well documented by Bodin and Krush [21], Christofides [22], and Lawler [23]. The property of unicursality is central to the CPP. A network is said to be unicursal or Eulerian if there exists a closed path containing each arc exactly once. A network is unicursal if and only if all its vertices have even degree, where a degree represents the number of edges incident at the vertex. If not, a unicursal graph can be constructed by augmenting the original network (adding edges to link odd-degree vertices). Eiselt et al. [7] formulate the CPP as an integer linear program (ILP) to get a graph so that all vertices have an even degree.

2.3 Rural Postman Problem.

RPP is a general case of the CPP where a subset of edges of a given network is required to be traversed at the least cost [8]. RPP reduces to a CPP, if all edges are required to be traversed. A conventional strategy for solving RPP is to first determine an augmentation of the graph to make it unicursal and then obtain an Eulerian cycle on the augmented network. The augmentation approach used by Edmonds and Johnson [24] is to find a shortest path between every pair of odd vertices. In specific, a complete graph is first formed, using odd vertices of the original graph. The distance of edges between each pair of odd vertices is computed as the length of the shortest path on the original graph connecting these two odd vertices. Next, a minimum distance matching is found for vertices of the complete graph of odd degree nodes and add these edges to the original graph. This results in an augmented graph, where every node has even degree, hence an Eulerian graph.

2.4 Minimum Matching Problem

The proposed method in this study includes a step that solves a minimum matching problem to get a unicursal graph from a given network. If graph does not contain an Eulerian cycle, it is achieved by finding a minimum matching in the given network. Edmond's Blossom Algorithm [25], the algorithm developed by Edmond in 1961 finds a matching in an undirected graph. Additionally, heuristics methods such as hyper-greedy and the factor of two have been proposed by Plaisted [26] to obtain perfect matching on graphs, that satisfies the triangle inequality. Other heuristic method for matchings from travelling salesperson tours obtained by the nearest-neighbor method [27].

CHAPTER 3: MODEL DESCRIPTION

This chapter presents a drone routing algorithm that provides a drone path covering the entire part of the distribution network. The algorithm aims to find the shortest (or minimal-distance) path such that all lines of the power distribution network experiencing outage are covered by the path. Consider a connected network $G(V, E)$ with a set of edges E and a set of vertices V where each edge $(i, j) \in E$ has a nonnegative distance $C_{(i,j)}$. The idea of the proposed algorithm is to augment G to a unicursal (a.k.a., Eulerian) network $G'(V, E')$, where E' is a super set of E. E' is constructed by adding a set of edges obtained from minimum-distance matching for the complete network consisting of only odd degree vertices. Then, an Eulerian tour of G' results in a drone path. To materialize this idea, we propose the following drone-path algorithm, which consists of three phases. Phase I is to extract the odd degree vertices from the network G. Phase II finds a solution to the minimum-distance matching problem of a complete network constructed with odd degree vertices using binary integer programming to obtain an Eulerian network. Phase III finds an Eulerian tour for the resulting network from Phase II. The overall procedure is presented in what follows.

3.1 Phase I: Extraction of Odd Vertices

In this phase, from a given power distribution network *G* (*V, E*), all odd degree vertices are extracted. Let *the vertex-edge incidence matrix* (a_{ve}), $v \in V$ and $e \in E$, defined by

$$a_{ve} = \begin{cases} 1 & \text{if edge } e \text{ and vertex } v \text{ are incident} \\ 0 & \text{otherwise.} \end{cases}$$

The sum $\sum_e a_{ve}$ represents the degree of vertex v. Let b_v be a binary value given by

$$b_v \equiv \sum_{e \in E} a_{ve} \ (mod\ 2),$$

where *mod* denotes modulo operation. Thus, b_v is zero when the degree of vertex v is even and one when the degree of vertex v is odd. Define $\overline{V} \equiv \{v \in V\colon\ b_v=1\}$. That is, $\overline{V} \subset V$ is the set of odd vertices of the network *G*. Note that $|\overline{V}|$ is an even number, where $|\cdot|$ denotes set cardinality.

3.2 Phase II: Minimum-Distance Matching

Consider an undirected complete network $\overline{G}(\overline{V}, \overline{E})$. In this phase, a minimum-distance matching in the network $\overline{G}$ is obtained. A minimum distance matching is a pairing of vertices such that each vertex is paired with exactly one other vertex so that the total distance of the edges connecting the pairs is minimized. A binary integer programming model to find a minimum-distance matching is presented below:

$\bar{C}_{(i,j)}$ is a distance of edge $(i, j) \in \bar{E}$ and $x_{(i,j)}$ is a binary variable that represents pairing of *i* and *j* (1 if paired, 0 otherwise).

Minimize $\quad \sum_{(i,j)\in E} \bar{C}_{(i,j)} x_{(i,j)}$ (1)

Subject to $\quad \sum_{j\in\overline{V}\setminus\{i\}} x_{(i,j)} = 1 \qquad \forall\, i \in \bar{V}$ (2)

$\qquad x_{(i,j)} \in \{0,1\} \qquad \forall\, (i,j) \in \bar{E}$ (3)

The objective function (1) minimizes the total distance of matching. Constraints (2) and (3) ensure that each vertex is paired with only one other vertex.

Let $\hat{E}$ denote the set of edges obtained from the minimum-distance matching. Then we construct a unicursal network $G'(V, E')$, where E' is the disjoint union of E and $\hat{E}$.

3.3 Phase III: Eulerian Tour

Once a unicursal network $G'(V, E')$ has been obtained, an Eulerian cycle on G' can be found using existing algorithms such as Fleury's algorithm or Hierholzer's algorithm. Hierholzer's algorithm works similar to Fleury's algorithm, but it is used for directed network. Since network G' is an undirected network, the Fleury's algorithm will be employed to find an Eulerian cycle. To explain how the Fleury's algorithm proceeds, there is a need for defining two terminologies; *bridge* and *non-bridge edge*. An edge is said to be a bridge, if removing it results in a disconnected network. Similarly, an edge is a non-bridge, if it does not disconnect the network when it is deleted. The basic principle of the Fleury's algorithm is to follow edges one at a time while always choosing a non-bridge if possible.

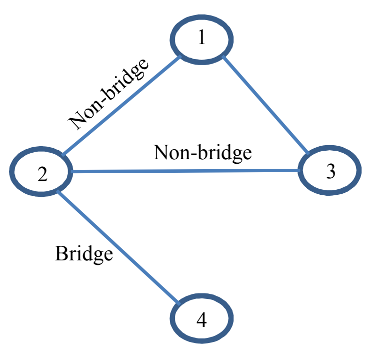


Figure 4: Example of bridge and non-bridge edges

For example, consider vertex 2 in the network shown in Figure 4. There are three edges that are incident at this vertex, (2,1), (2,3), and (2,4). Edge (2,4) is a bridge while (2,1) and (2,3) are non-bridges. Note that, if one deletes the bridge (2,4), then the rest of network becomes disconnected. On the other hand, if a non-bridge is deleted, the rest of the network is still connected, and hence, accessible.

The steps of the Fleury's algorithm can be summarized as follows:

Step 1: Given $G'(V, E')$, select $i \in V$, and initialize a sequence $S = \{i\}$.

Step 2: If E'= Ø, stop, with S. Otherwise, go to Step 3.

Step 3: Let $V_i = \{ j \in V : (i, j)$ is incident at i }.

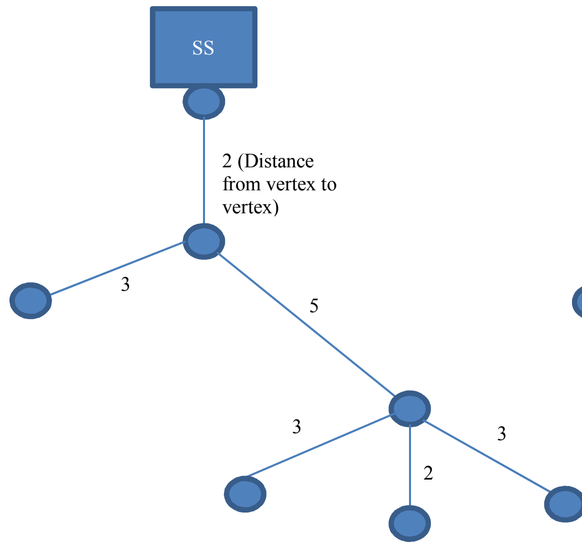
Step 4: Select $k \in V_i$. If (i, k) is a non-bridge or $|V_i| = 1$, then go to step 5.

Otherwise, update $V_i \leftarrow V_i \setminus \{ k \}$ and repeat step 4.

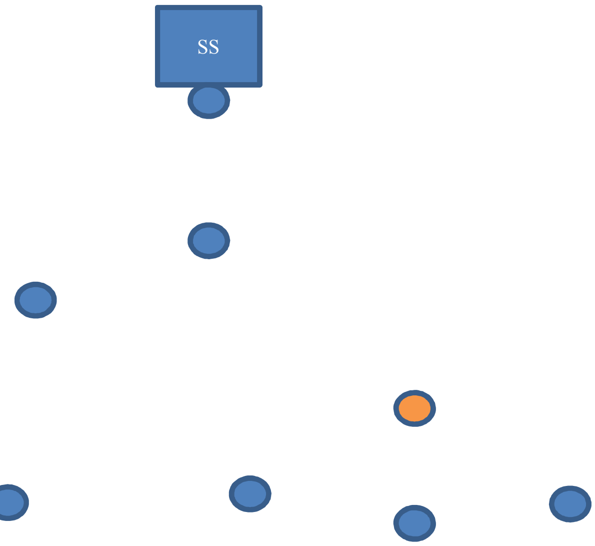
Step 5: Update $E' \leftarrow E' \setminus \{(i, k)\}$, add k to S, and let $i \leftarrow k$, and return to step 2.

From above steps, an Eulerian tour is constructed on G'. The following example demonstrates the three-phase procedure to find a drone path.

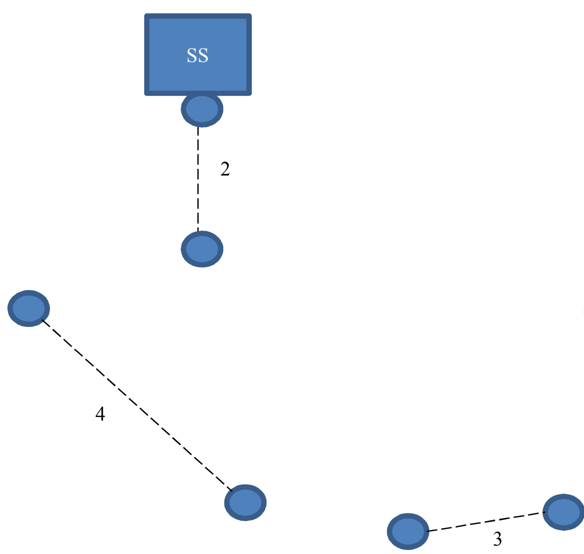
Example 1. Consider the network shown in Figure 5(a), G (V, E), which has seven vertices and six edges. Suppose that the substation vertex is in the top. The network has six odd degree vertices and one even degree vertex as shown in Figure 5(b), where the even degree vertex is marked with orange dot. Figure 5(c) is the result of minimum-distance matching for the complete network $\bar{G}(V, \bar{E})$. These three edges are added to the original network to form $G'(V, E')$ as in Figure 5(d). Note that this network is unicursal. Figure 5(e) shows an Eulerian path starting from and ending at the substation vertex.



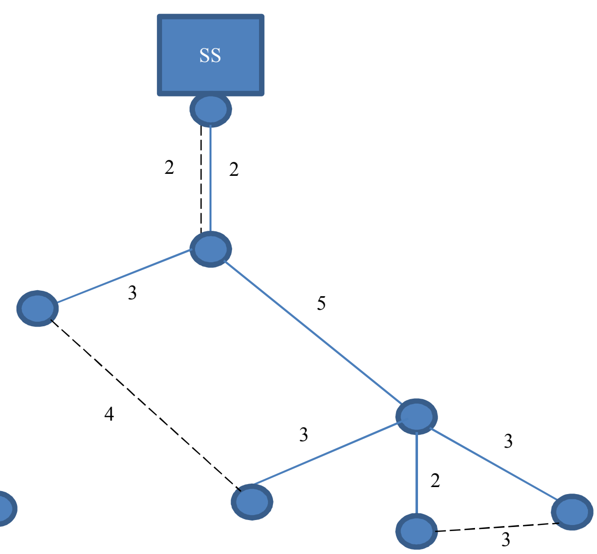
(a) Original network $G\ (V, E)$



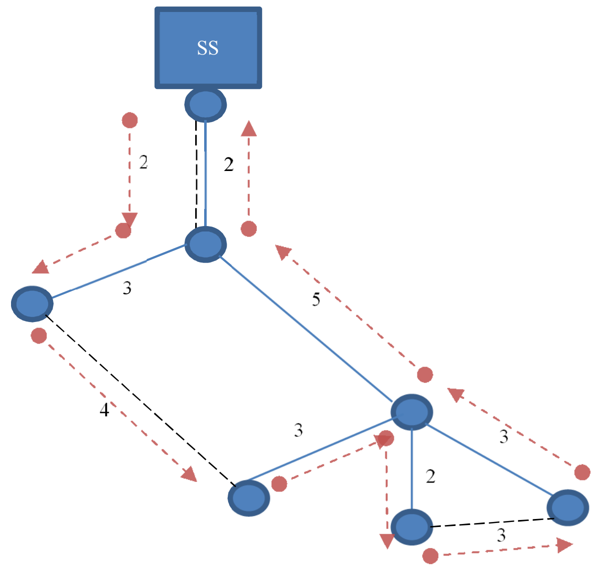
(b) Odd and even degree vertices



(c) Minimum-distance matching for $\bar{G}(V, \bar{E}\ )$



(d) Augmented network $G'(V, E')$



(e) Eulerian path

Figure 5: Illustrative example of the proposed three-phase algorithm

Once a drone path is obtained as shown in Figure 5(e), flight plan is downloaded into the drone controller to inspect the given network. Since drones are battery operated, flight times are limited by battery capacities. For example, as assumed later in Chapter 4, consider maximum flight of 16 minutes and average speed of 7 miles/hour of the DJI Phantom [28], which results a total flight distance of 1.8 miles. If the distance of the flight path is too long, the battery has to be replaced at certain points of the path. Let max_dist denote the maximum distance that a drone can fly with a fully charged battery.

Furthermore, let $\{v_{(1)}, v_{(2)}, v_{(3)}, .., v_{(K)}\}$ denote the sequence representing the drone path obtained from the three-phase algorithm. That is, starting from vertex $v_{(1)}$, the drone visits vertices following the sequence. The following procedure is used to identify battery replacement points.

3.4 Battery Replacement Procedure

Step 1: Initialize i=2, dis =0, and BR = {}.

Step 2: If $i > K$ then stop with BR, Otherwise,

dist ← dist + $C_{(v_{(i-1)}, v_{(i)})}$.

Step3: If dist > max_dist, then

Add $v_{(i-1)}$ to BR, then reset dist =0, and return to Step 2, Otherwise, go to Step 4

Step 4: i←i+1. Return to step 2.

The resulting BR represents the set of battery replacement vertices. Figure 6 shows a flowchart of the proposed procedure for battery replacement.

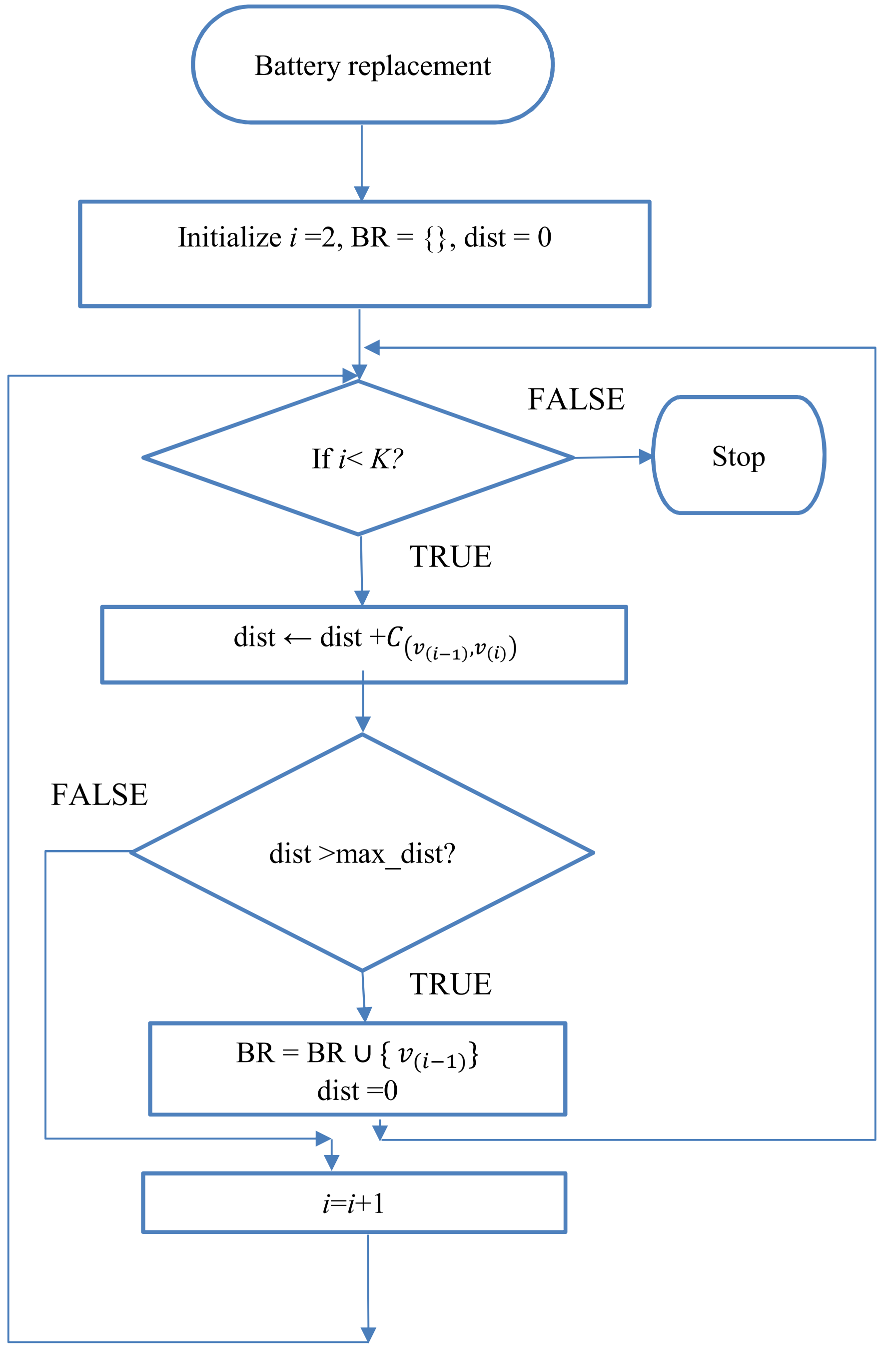


Figure 6: Proposed procedure for battery replacement

3.5 Summary of Drone Routing Algorithm

This section provides a summary of the entire drone routing algorithm.

Step 1: Input network data $G\ (V, E)$ for an outage area with X and Y coordinates of vertices.

Step 2: Calculate the distance C_{ij} for each edge $(i, j) \in E$.

Step 3: Calculate degrees of vertices of network $G\ (V, E)$.

Step 4: Extract odd degree vertices to create a set $\bar{V}$.

Step 5: Construct an undirected complete network $\bar{G}(\bar{V}, \bar{E})$.

Step 6: Calculate the distance $\bar{C}_{ij}$ for edge $(i, j) \in \bar{E}$.

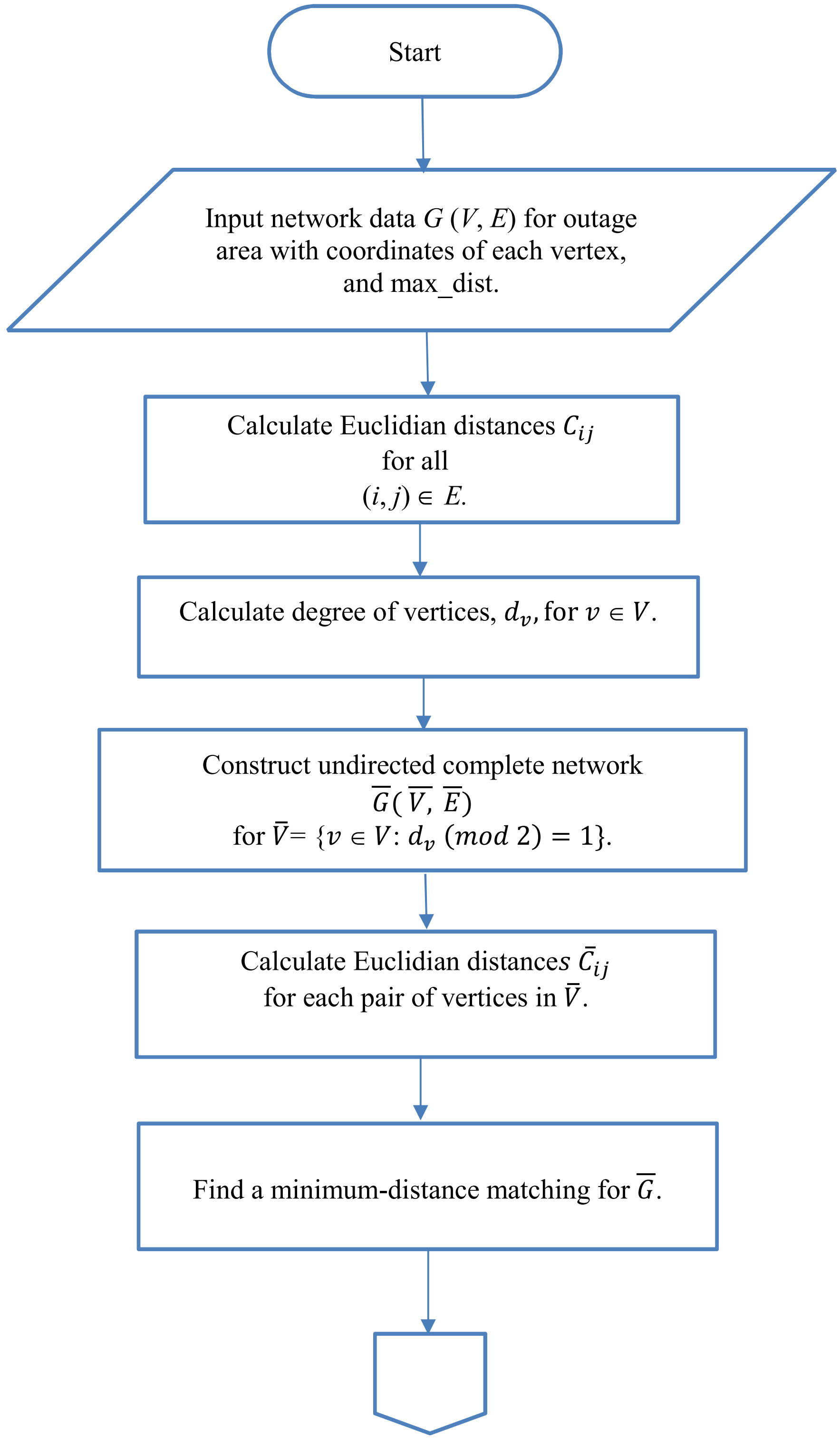
Step 7: Find a minimum-distance matching for $\bar{G}$ and let $\hat{E}$ be the edge set corresponding to the matching.

Step 8: Construct a unicursal network $G'(V, E')$ where E' is the disjoint union of E and $\hat{E}$.

Step 9: Find a Eulerian path $\mathbb{P} = \{v_{(1)}, v_{(2)}, v_{(3)}, \dots, v_{(K)}\}$ for G'.

Step 10: Run the battery replacement procedure to identify the battery replacement points in $\mathbb{P}$.

Figure 7 flowchart shows the proposed drone routing algorithm.


Start
Input network data G (V, E) for outage area with coordinates of each vertex, and max_dist.
Calculate Euclidian distances C_{ij} for all $(i, j) \in E$.
Calculate degree of vertices, d_v, for $v \in V$.
Construct undirected complete network $\overline{G}(\overline{V}, \overline{E})$ for $\overline{V} = \{v \in V: d_v \ (mod\ 2) = 1\}$.
Calculate Euclidian distances $\bar{C}_{ij}$ for each pair of vertices in $\overline{V}$.
Find a minimum-distance matching for $\overline{G}$.

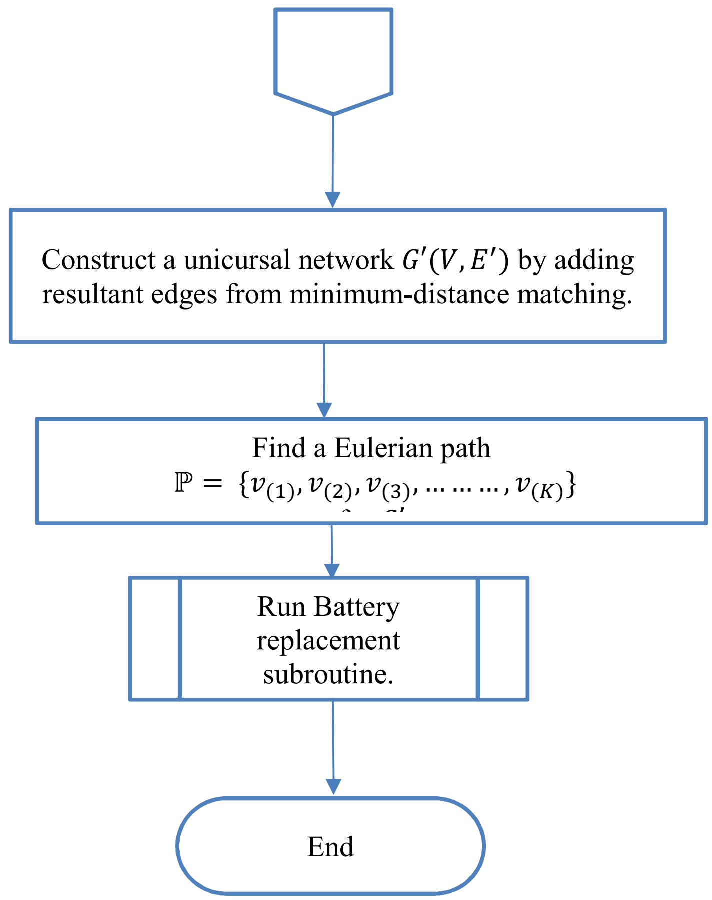


Figure 7: Proposed procedure for drone routing algorithm

CHAPTER 4: CASE STUDY- KUDZU FEEDER

To demonstrate its application in a realistic setting, the drone routing algorithm is applied to a real feeder network. The input data is composed of vertices and their corresponding (x, y) coordinates, and edges that correspond to power lines. The network used in this case-study consists of 248 vertices and 248 edges. This feeder is referred to as 'Kudzu' (Figure 8). The total distance of all edges in the Kudzu network is 58,254 feet. Each dot represents a vertex of the network at given coordinates and edges are represented by line connecting between vertices.

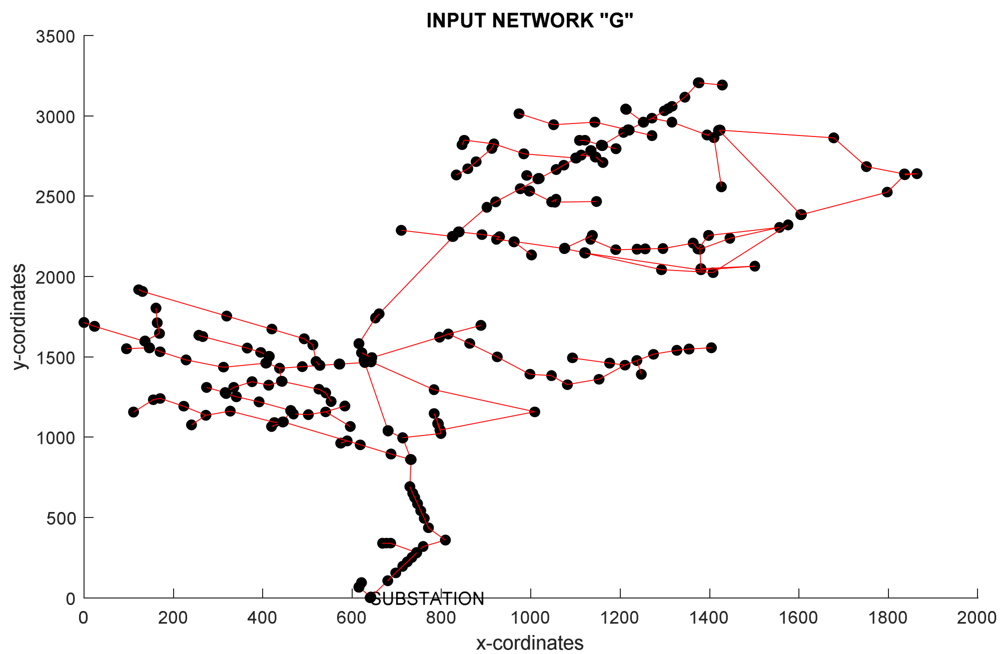


Figure 8: Case study - Kudzu feeder

In the first phase, odd degree vertices are identified. Figure 9 shows all vertices of the Kudzu feeder network. Dots which are filled represent odd degree vertices and empty dots represent even degree vertices. The Kudzu feeder has a total of 176 even degree vertices and 72 odd degree vertices.

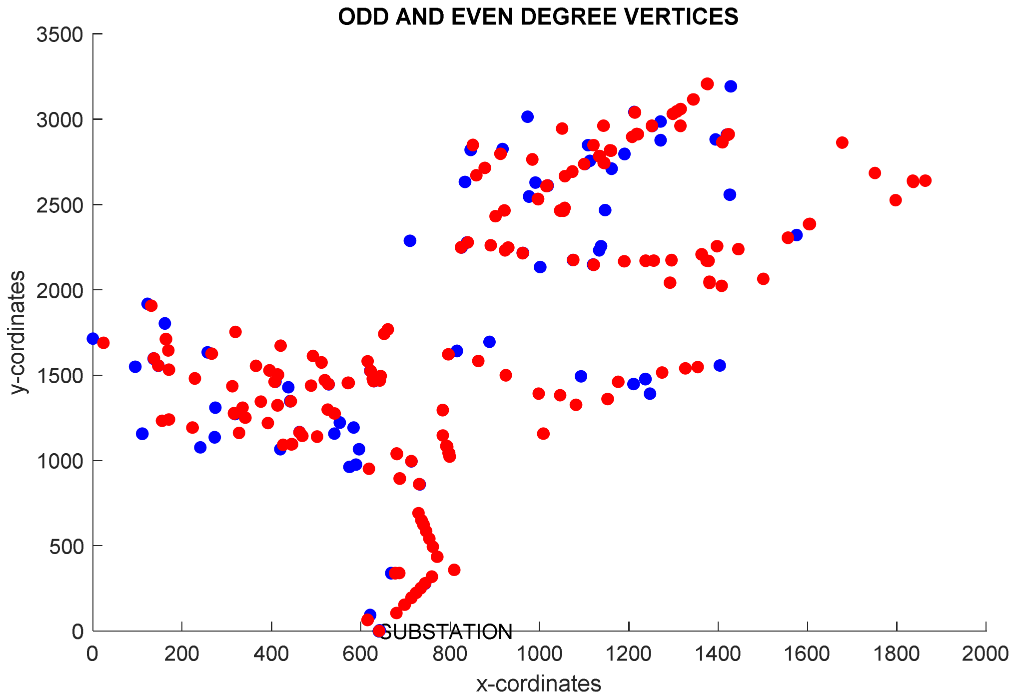


Figure 9: Extraction of odd and even vertices- Kudzu feeder

As a result of phase I, an undirected complete network $\overline{G}(\overline{V}, \overline{E})$ is formed, where $\overline{V}$ represents odd degree vertices and $\overline{E}$ represents edges connecting all odd vertices. Figure 10 shows only odd degree vertices.

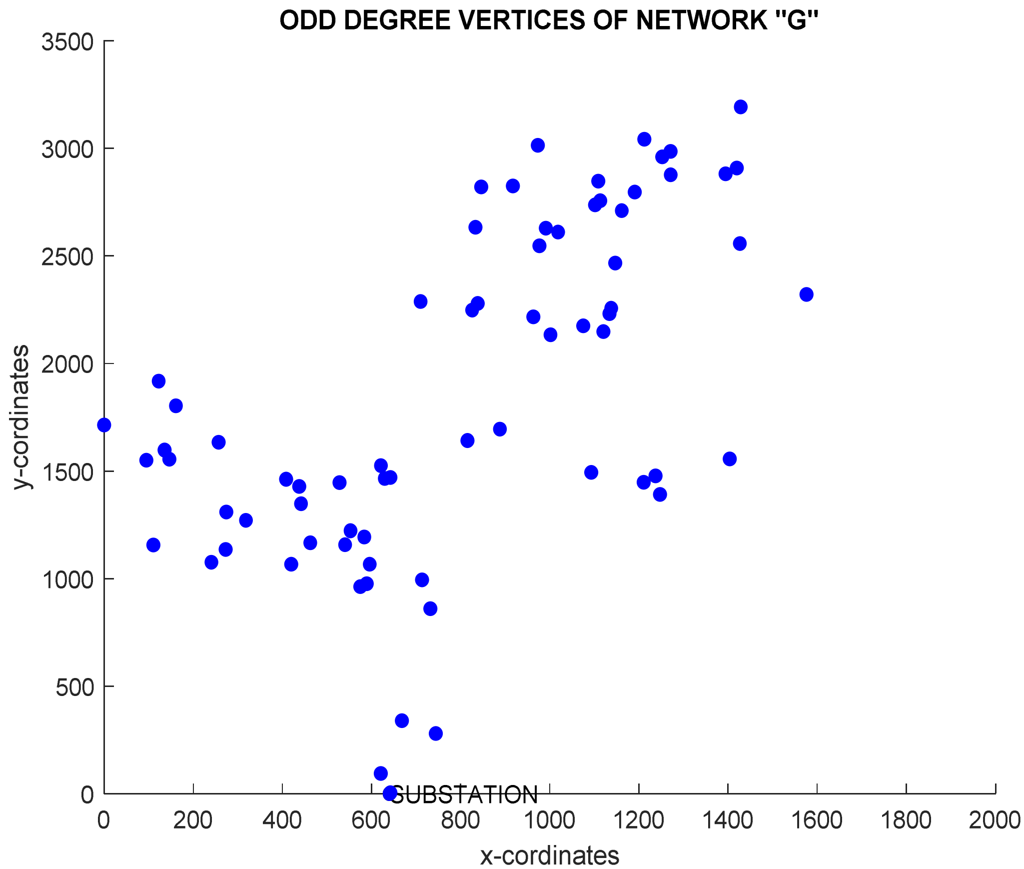


Figure 10: Odd degree vertices-Kudzu feeder

A binary integer programming problem is solved to find a minimum distance matching for $\overline{G}$. Figure 11 is the result of the minimum distance matching (Phase II), where 36 additional edges are obtained.

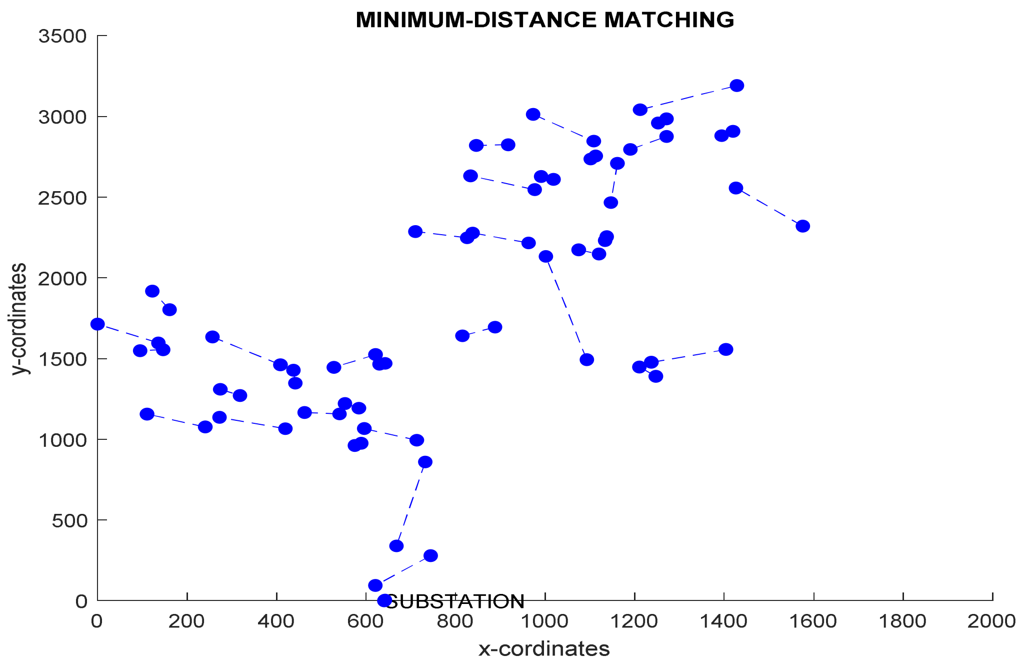


Figure 11: Matching solution to $\bar{G}$ - Kudzu feeder

These edges are added to the original network $G\ (V, E)$ to construct $G'(V, E')$ as in Figure 12. Phase–III is applied to obtain a drone path.

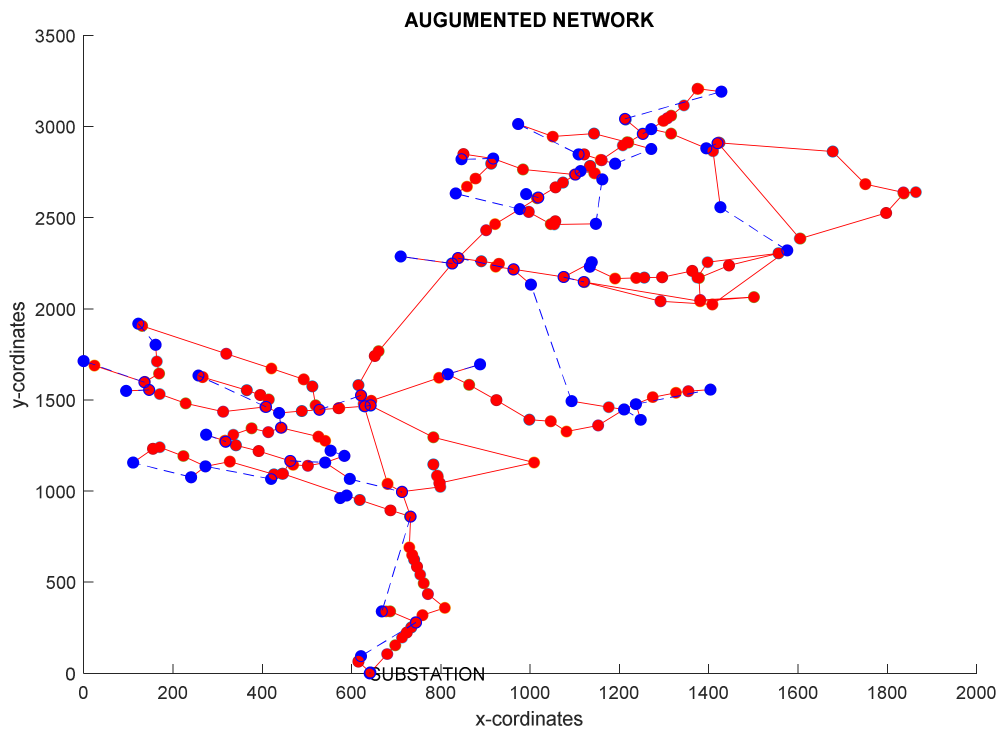


Figure 12: Augmented network with added edges-Kudzu feeder

For the case study, a specific commercial drone model, called DJI Phantom 3 Pro [28], is considered to characterize the drone specification. DJI Phantom 3 Pro has a maximum flight time of 23 minutes, which means the battery of the drone has to be replaced well before 23 minutes of flight time. It is assumed that the flight time must not exceed the 16 minutes before replacing the battery. Since the maximum flight time of the drone can be affected by temperature, wind speed, flying style, etc. during the flight, users of DJI Phantom recommend 16 minutes flight time instead of the nominal maximum flight time of 23 minutes [29]. Besides, the average speed of the drone is assumed to be 7 miles/hour which gave good visual inspection to a point of interest in a location based on various flight testing. When other types of drones with different characteristics are used, speed and flight time can be adjusted accordingly, and this will result in change in damage assessment time, total travel time, and battery replacement locations. Based on these assumptions, it is calculated that a drone can travel a total distance of 1.8 miles when fully charged. Since the drone can travel the maximum of 1.8 miles, the flight path is divided into multiple smaller circuits, each of which can be assessed by a single flight of the drone. The Kudzu feeder has a drone flight path that amounts the total distance of 13.215 mile (69,775 ft.). In this situation, the drone cannot inspect the complete Kudzu feeder network and battery has to be replaced at some points of the path. As the result of the battery replacement procedure vertices 177, 231, 128, 189, 56, 87, 180 are identified as battery replacement points. Therefore, there are eight flight circuits. These eight circuits are shown in Figure 13. Table 1, shows number of battery replacement points, keeping flight time of 16 minutes and varying speed of drone.

Table 1: Results of Kudzu feeder network

Network Name	Start Vertex	End Vertex	Time (min)	Distance (miles)
Kudzu Network	134.00	134.00	183.27	13.22
Segment-1	134.00	177.00	15.81	1.84
Segment-2	177.00	231.00	14.98	1.75
Segment-3	231.00	128.00	15.23	1.78
Segment-4	128.00	189.00	15.20	1.77
Segment-5	189.00	56.00	15.91	1.86
Segment-6	56.00	87.00	15.31	1.79
Segment-7	87.00	180.00	15.89	1.85
Segment-8	180.00	134.00	4.93	0.58
	Total Flight Time		113.27	13.22
	Total Battery Replacement Time		70.00	
	Total Inspection Time		183.27	

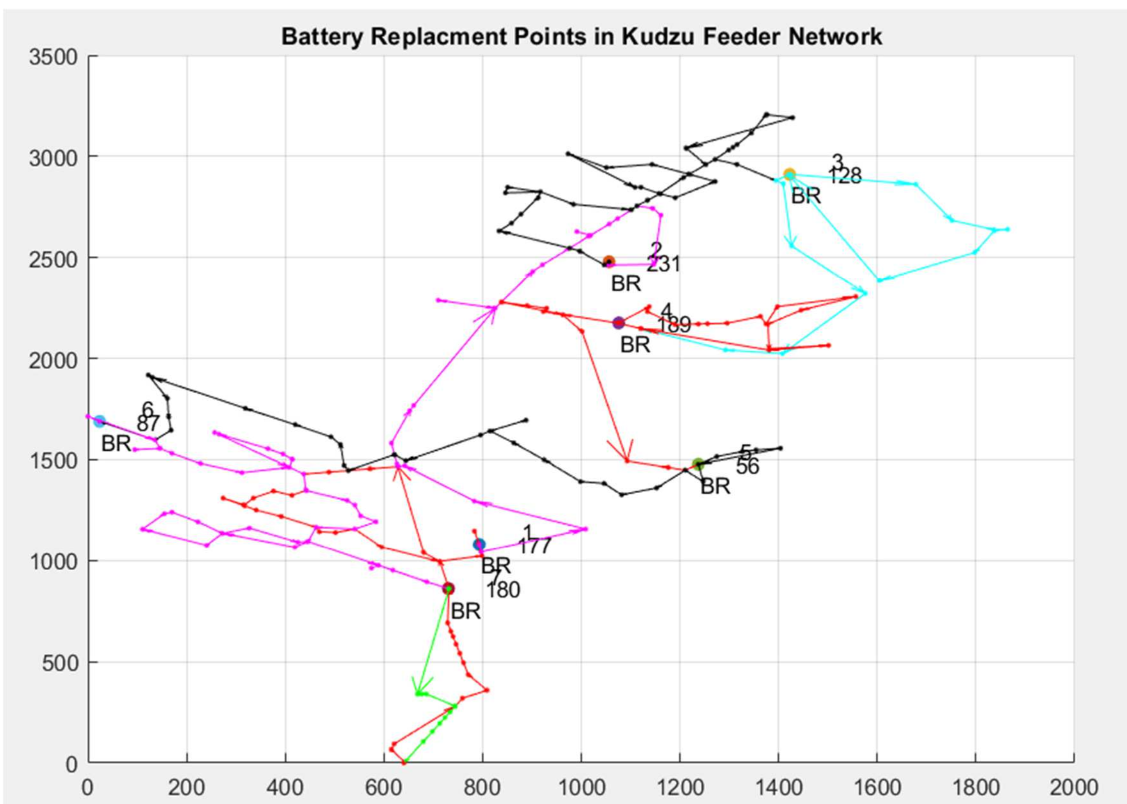
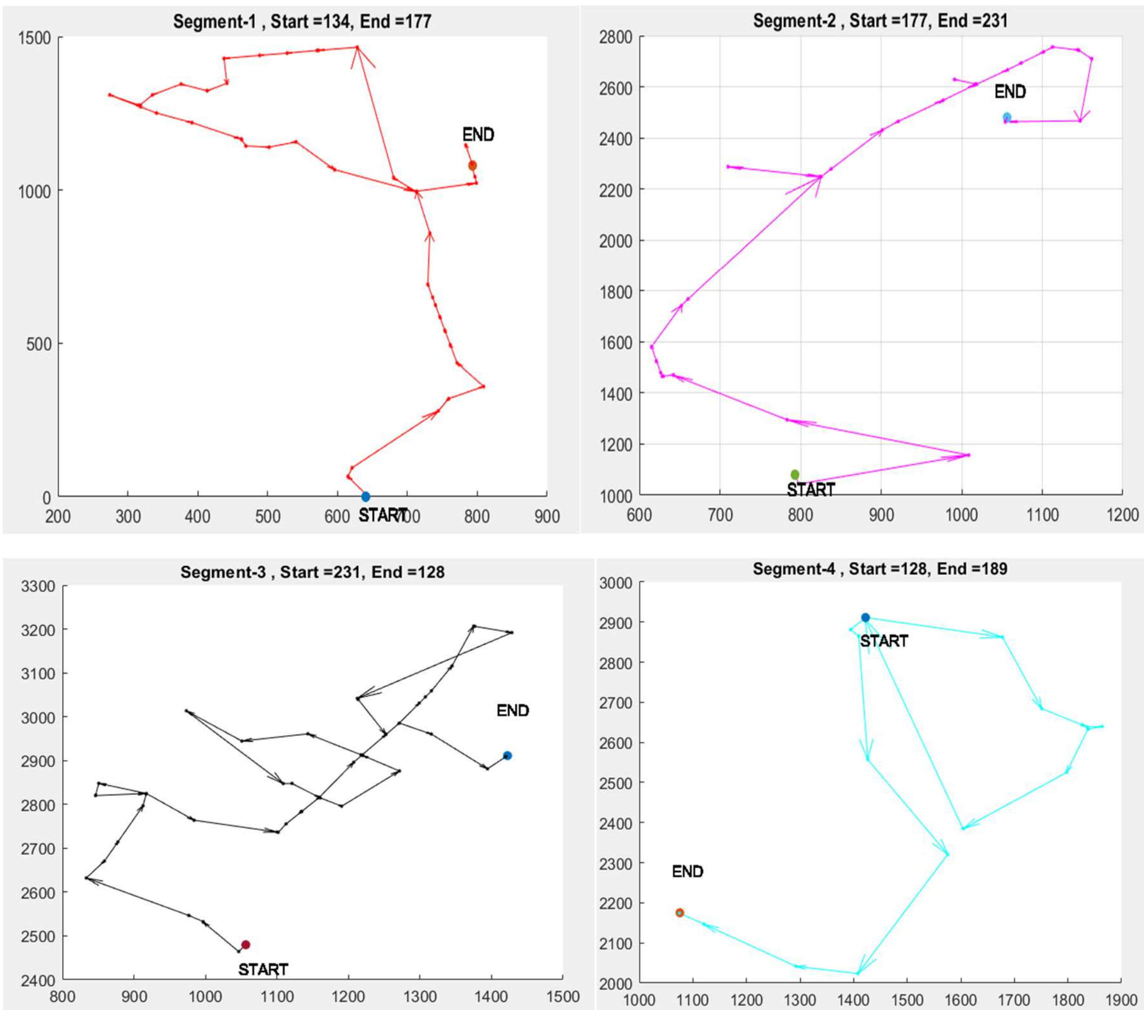


Figure 13: Segments of drone flight with battery replacement

Figure 14 shows the drone path divide into eight segments, where start and end points of each segment are shown with large filled dots. Since battery has to be replaced at these points, 10 minutes of battery replacement time is considered. Table 1 shows the flight time and distance of each segment along with its start and end vertices.



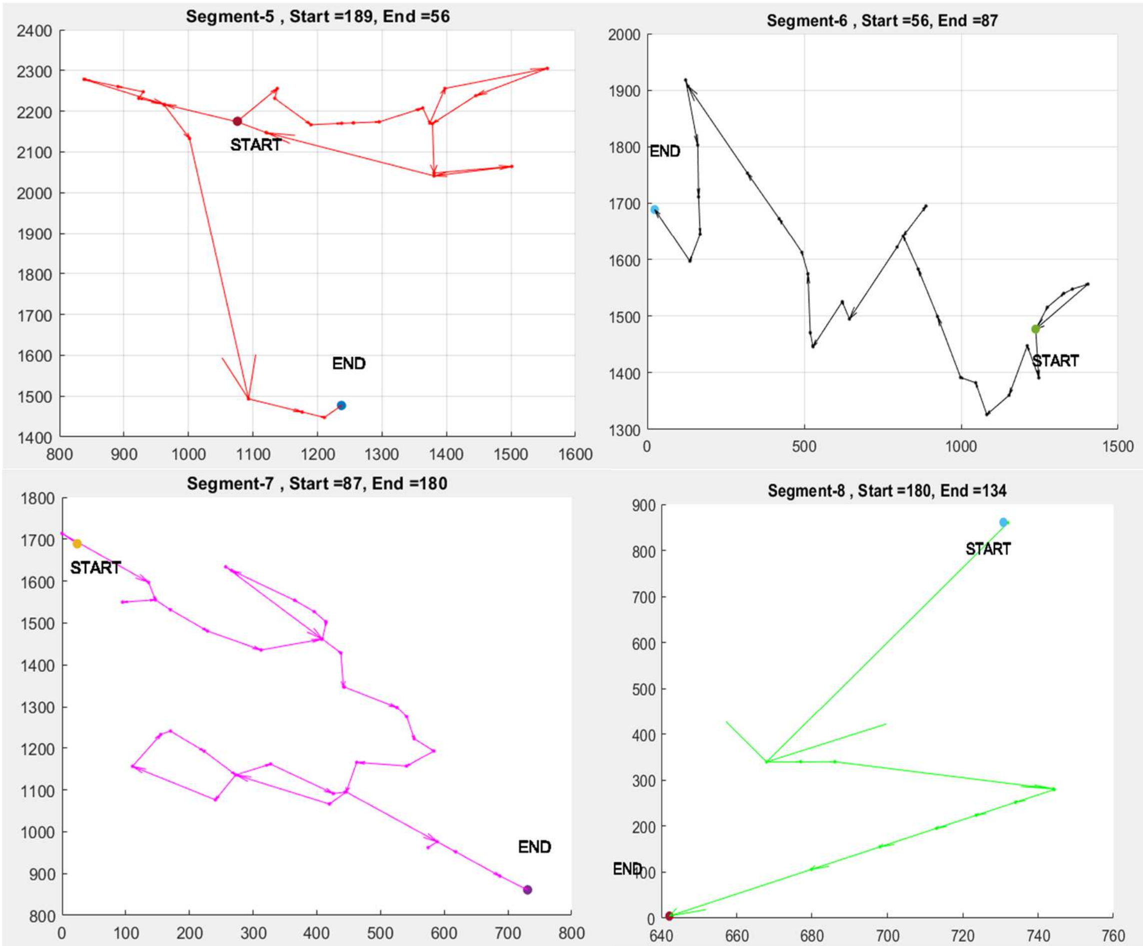


Figure 14: Eight segments of the drone path with start and end vertices

Table 2: Results of Kudzu feeder network based on varying speed of drone

Speed	Time	Number of Segments	Total Inspection Time
7mph	1.87	8	183.27
9mph	2.40	6	158.10
11mph	2.93	5	142.08
13mph	3.47	4	130.99
15mph	4.00	4	122.86
17mph	4.53	3	116.64

As mentioned earlier, when the speed of drone is adjusted, the total inspection time will be changed. Table 2, displays the results of various speeds ranging from 7 mph to 17 mph. It should be noted that the flight path remains the same.

CHAPTER 5: INTEGRATION OF DRONE ASSESSMENT WITH CREW RESTORATION SCHEDULING

From the drone routing algorithm proposed in Chapter 3, a drone flight path to inspect a specific or entire part of a single circuit is available. However, HILF events typically affect large areas, where multiple circuits experience power outage. Hence, the overall damage assessment time also depends on the assessment sequence of those multiple circuits.

This chapter investigates sequencing methods for multiple circuits given the number of damage assessment units. Note that damage assessment time of each affected circuit can be estimated from the drone flight path obtained by the drone routing algorithm. Furthermore, suppose that estimated travel times between affected circuits as well as estimated travel times from operation center (OC) to affected circuits are available. Assuming the same capability of damage assessors, scheduling damage assessors can be considered as a parallel machine scheduling with sequence-dependent setup times, where identical machines are scheduled to process multiple jobs with known processing times. We will particularly investigate two sequencing rules, Longest Processing Time (LPT) and Shortest Processing Time (SPT) rules depending on the performance criteria. The LPT rule assigns jobs having longer processing times first, while SPT rule does the opposite. When setup times are ignored, the LPT rule provides an approximation when the minimum makespan, the time at which the assessment of the entire system is completed, is considered as the decision criterion. On other hand, the SPT rule is known to minimize the sum of all completion times, where the completion time of a circuit represents the time when the assessment of the circuit is finished.

Let T_A^k be the estimated damage assessment time of circuit k calculated from the drone routing algorithm, T_r^k be the travel time from OC to circuit k, and T_l^k be the travel time from circuit l to circuit k.

Let K and N denote a set of circuits to be inspected and the set of available assessment units, respectively. The goal is to find job sequences of damage assessment units, A_i , $i \in N$. Let l_i denote the last job assigned in sequence A_i. Considering sequence-dependent setup times (i.e., travel times), variants of these rules are presented.

5.1 Modified Longest Processing Time Rule

The proposed modification of the LPT procedure is described in what follows:

Step 1: Initialize C_i =0 and $A_i = \emptyset$ for $i \in N$.

Set $T_t^k = T_r^k + T_A^k$ for $k \in K$. Put $K_c = K$.

Step 2: If $K_c = \emptyset$, stop with A_i, $i \in N$.

Otherwise, proceed to Step 3.

Step 3: Let $i^* = \text{argmin}\{C_i : i \in N\}$.

If $C_{i^*} \neq 0$, update $T_t^k = T_{l_{i^*}}^k + T_A^k$ for $k \in K_c$.

Step 4: Let $k^* = \text{argmax}\{T_t^k : k \in K_c\}$. Update

$C_{i^*} \leftarrow C_{i^*} + T_t^{k^*}$, $A_{i^*} \leftarrow A_{i^*} \cup \{k^*\}$, and $K_c \leftarrow K_c \setminus \{k^*\}$.

Return to Step 2.

The following example presents how this modified of the LPT rule is applied. Consider five circuits to be inspected. Initial values of T_t^k is shown in Table 3. Distance data between circuits is presented in Table 4. Suppose that there are three damage assessment units available for inspection.

Table 3: Assessment times and travel times from the OC to each circuit.

k	1	2	3	4	5
T_A^k	46	58	72	87	104
T_r^k	9	12	5	3	6

Table 4: Distance between Circuits.

	1	2	3	4	5
1	0	7	6	4	12
2	7	0	11	6	8
3	6	11	0	4	10
4	4	6	4	0	6
5	12	8	10	6	0

Iteration 1:

Step 1: Let $N = \{1,2,3\}$ be the set of damage assessment units and $K = \{1,2,3,4,5\}$ be the set of circuits to be inspected.

Initialize $C_1 = 0, C_2 = 0, C_3 = 0, A_1 = \emptyset, A_2 = \emptyset$, and $A_3 = \emptyset$.

$T_t^1 = 46 + 9 = 55$, $T_t^2 = 58 + 12 = 70$, $T_t^3 = 72 + 5 = 77$, $T_t^4 = 87 + 3 = 90$, $T_t^5 = 104 + 6 = 110$, and $K_c = \{1,2,3,4,5\}$

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* =argmin {0,0,0} results in i^*= 1 and $C_1 = 0$. Since $C_1 = 0$, move to Step 4.

Step 4: k^* = argmax $\{55,70,77,90,110\}$, results in k^*=5. Update $C_1 \leftarrow C_1 + T_t^5 = 0 + 110 = 110$, $A_1 = \{5\}$, and $K_c = \{1,2,3,4\}$.

Iteration 2:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* =argmin $\{110,0,0\}$ results in i^*= 2 and $C_2 = 0$. Since $C_2 = 0$, move to Step 4.

Step 4: k^* = argmax $\{55,70,77,90\}$, results in k^*=4. Update $C_2 \leftarrow C_2 + T_t^4 = 0 + 90 = 90$, $A_2 = \{4\}$, and $K_c = \{1,2,3\}$.

Iteration 3:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* =argmin $\{110,90,0\}$ results in i^*= 3 and $C_3 = 0$. Since $C_3 = 0$, move to Step 4.

Step 4: k^* = argmax $\{55,70,77\}$, results in k^*=3. Update $C_3 \leftarrow C_3 + T_t^3 = 0 + 77 = 77$, $A_3 = \{3\}$, and $K_c = \{1,2\}$.

Iteration 4:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* =argmin $\{110,90,77\}$ results in i^*= 3 and $C_3 = 77$. Since $C_3 \neq 0$, it updates total estimated assessment time of circuits to be inspected, i.e., $K_c = \{1,2\}$. Note that l_{i^*}=3.

Circuit-1: $T_t^1 = T_3^1 + T_A^1$= 6 + 46=52

Circuit-2: $T_t^2 = T_3^2 + T_A^2$= 11+58=69

Step 4: k^* = argmax $\{52,69\}$, results in k^*=2. Update $C_3 \leftarrow C_3 + T_t^3 = 77 + 69 = 146$, $A_3 = \{3,2\}$, and $K_c = \{1\}$.

Iteration 5:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{110,90,146\}$, then results in i^*= 2, and $C_2 = 90$. Since $C_2 \neq 0$, it updates total estimated assessment time of circuits to be inspected, in this case $K_c = \{1\}$. Note that l_{i^*}=4.

Circuit-4: $T_t^4 = T_1^4 + T_A^1$= 4+46=50

Step 4: k^* = argmax $\{50\}$, results in k^*=1. Update $C_2 \leftarrow C_2 + T_t^4 = 90 + 50 = 140$,

$A_2 = \{4,1\}$, and $K_c = \emptyset$.

At the end of the fifth iteration, it goes to Step 2. Since K_c set is empty it stops and returns C_i and A_i.

After applying the above procedure, the job sequence of damage assessment units and their estimated time for travel and assessment are obtained as in Figure 15.

Results:

$C_1 = 110, C_2 = 140, C_3 = 146, A_1 = \{5\}, A_2 = \{4,1\}, A_3 = \{3,2\}$

1. Makespan: 146
2. Total completion time: 566

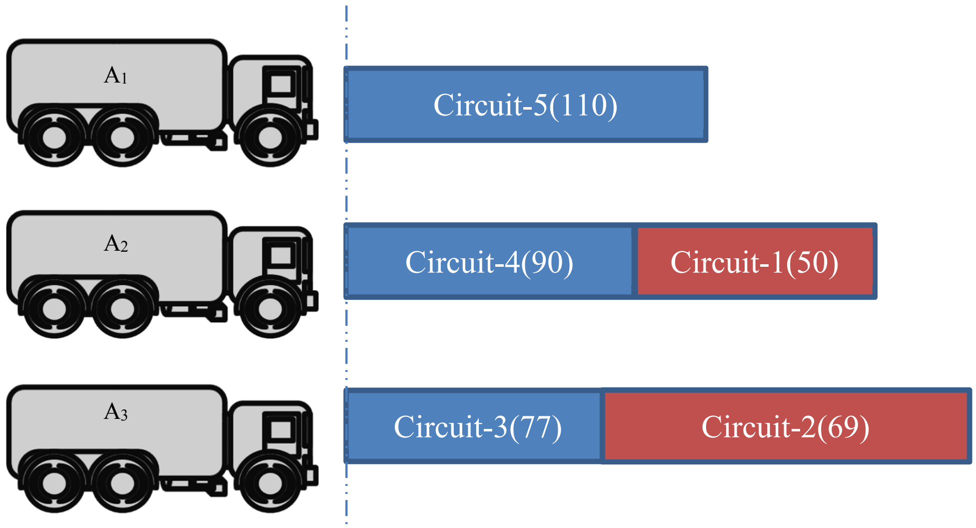


Figure 15: Job sequence of damage assessment units the modified using LPT rule (with associated circuits, and estimated time for travel and damage assessment in parenthesis)

5.2 Modified Shortest Processing Time Rule

As mentioned earlier, the SPT rule assigns jobs having shortest processing times first. The rule is modified to accommodate sequence-dependent setup times. The main difference between the modified LPT and the modified SPT in the algorithm is that $k^* = \text{argmax}\{T_t^k: k \in K_c\}$ is replaced with $k^* = \text{argmin}\{T_t^k: k \in K_c\}$ in Step 4.

The same example is used to illustrate the modified SPT rule.

Iteration 1:

Step 1: Let $N = \{1,2,3\}$ be the set of damage assessment units and $K = \{1,2,3,4,5\}$ be the set of circuits to be inspected.

Initialize $C_1 = 0, C_2 = 0, C_3 = 0$ and $A_1 = \emptyset, A_2 = \emptyset$, and $A_3 = \emptyset$.

$T_t^1 = 46 + 9 = 55$, $T_t^2 = 58 + 12 = 70$, $T_t^3 = 72 + 5 = 77$, $T_t^4 = 87 + 3 = 90$, $T_t^5 = 104 + 6 = 110$, and $K_c = \{1,2,3,4,5\}$

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{0,0,0\}$ results in i^*= 1 and $C_1 = 0$. Since $C_1 = 0$, move to Step 4.

Step 4: k^* = argmin $\{55,70,77,90,110\}$, results in k^*=1. Update $C_1 \leftarrow C_1 + T_t^1 = 0 + 55 = 55$, $A_1 = \{1\}$ and $K_c = \{2,3,4,5\}$.

Iteration 2:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{55,0,0\}$ results in i^*= 2 and $C_2 = 0$. Since $C_2 = 0$, move to Step 4.

Step 4: k^* = argmin $\{70,77,90,110\}$ results in k^*=2. Update $C_2 \leftarrow C_2 + T_t^2 = 0 + 70 = 70$, $A_2 = \{2\}$, and $K_c = \{3,4,5\}$.

Iteration 3:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{55,70,0\}$ results in i^*= 3 and $C_3 = 0$. Since $C_3 = 0$, move to Step 4.

Step 4: k^* = argmin $\{77,90,110\}$ results in k^*=3. Update $C_3 \leftarrow C_3 + T_t^3 = 0 + 77 = 77$, $A_3 = \{3\}$, and $K_c = \{4,5\}$.

Iteration 4:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{55,70,77\}$ results in i^*= 1 and $C_1 = 55$. Since $C_1 \neq 0$, it updates total estimated assessment time of circuits to be inspected, in this case $K_c = \{4,5\}$. Note that l_{i^*}=1.

Circuit-4: $T_t^4 = T_1^4 + T_A^4$= 4+87=91

Circuit-5: $T_t^5 = T_1^5 + T_A^5$= 12 +104=116

Step 4: k^* = argmin $\{91,116\}$ results in k^*=4. Update $C_1 \leftarrow C_1 + T_t^1 = 55 + 91 = 146$, $A_1 = \{1,4\}$, and $K_c = \{5\}$.

Iteration 5:

Step 2: Since K_c is not empty, it proceeds to Step 3.

Step 3: i^* = argmin $\{146,70,77\}$, then results in i^*= 2, and $C_2 = 70$. Since $C_2 \neq 0$, it updates total estimated assessment time of circuits to be inspected, in this case $K_c = \{5\}$. Note that l_{i^*}=2.

Circuit-5: $T_t^5 = T_2^5 + T_A^5$= 8+104=112

Step 4: k^* = argmax $\{112\}$, results in k^*=5. Update $C_2 \leftarrow C_2 + T_t^5 = 70 + 112 = 182$, $A_2 = \{2,5\}$, and $K_c = \emptyset$.

At the end of the fifth iteration, it goes to Step 2. Since K_c set is empty it stops and returns C_i and A_i.

After implementing the above procedure, the job sequence of damage assessment units and their estimated time for travel and assessment is obtained as in Figure 16.

Results:

$C_1 = 146, C_2 = 182, C_3 = 77$ $A_1 = \{1,4\}, A_2 = \{2,5\}, A_3 = \{3\}$

1. Makespan: 182
2. Total completion time: 530

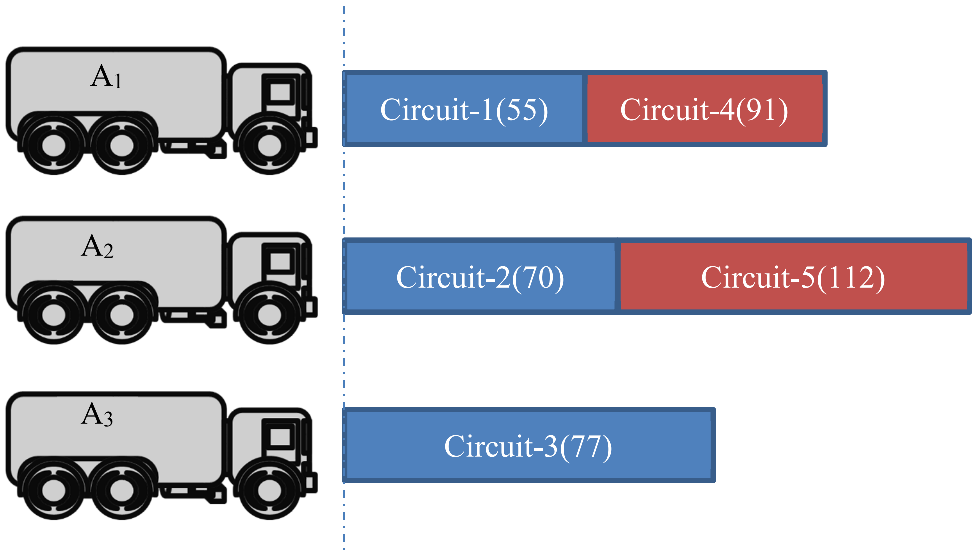


Figure 16: Job sequence of damage assessment units using the modified SPT rule (with associated circuits, and estimated time for travel and damage assessment time in parenthesis)

Table 5: Comparison of performance measures of the modified LPT and the modified SPT

	Makespan	Total Completion
LPT	146.00	566.00
SPT	182.00	530.00

Figure 17 illustrates the implication of performance measures; makespan and total completion time based on assessment unit routing.

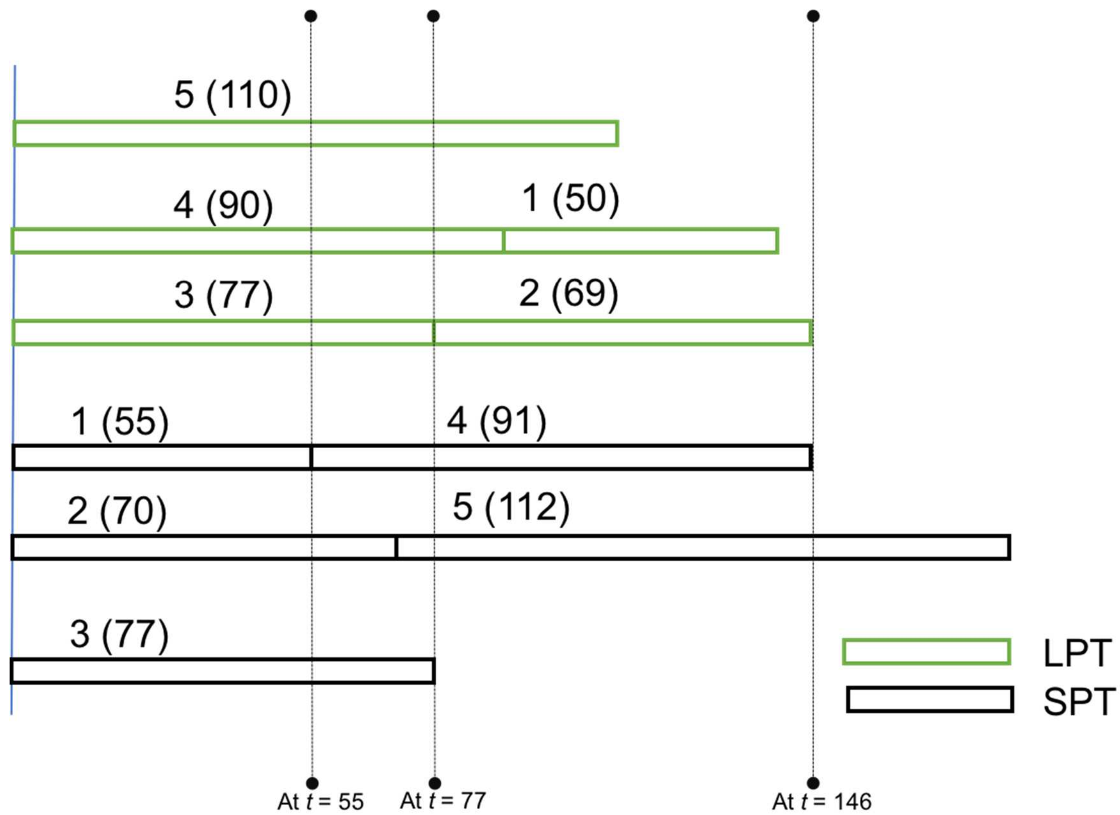


Figure 17: Comparison between the modified LPT and the modified SPT

If it is desired to have quick damage assessment in an early stage, it is recommended to use the modified SPT, because circuits with the least damage assessment times are assessed first. However, if utility wants to finish the overall damage assessment of all affected circuits as quickly as possible, it is recommended to use the modified LPT.

For example, consider at time t =55 in Figure 17, the first assessment is being finished in the modified SPT, whereas in the modified LPT assessment is still in progress without completing assessment of any circuit. Subsequently, at time t = 77, two assessments are finished in the modified SPT and one assessment in the modified LPT.

Hence, the modified SPT may provide a more number of circuits for which assessment is completed in the early stage. At the end, however, the modified LPT finishes the assessment on all five circuits at time t = 146, while the modified SPT still assessing the last circuit.

CHAPTER 6: CONCLUSION AND FUTURE STUDY

This chapter presents the conclusion and provides a direction for future research that can be investigated in the field of system restoration process using drone technology.

6.1 Conclusion

High impact low frequency (HILF) events have created severe disruptions in power distribution systems. In this thesis, we consider a damage assessment process in an effort to minimize the restoration time. Exploiting agility and accessibility of drone technology, we propose a three-phase algorithm that provides an efficient drone flight path. In addition, the proposed algorithm is integrated with the overall schedule for the damage assessment. As a result, this study provides a systematic procedure for damage assessment utilizing agile drone technology along with an efficient flight path for the drone.

6.2 Future Study

This thesis considers a static decision that needs to be made before the restoration process begins. As the damage assessment proceeds, real-time information becomes available, and there is a need for real-time decision making in scheduling damage assessors. Such real-time decision must quickly reflect any deviation from the original input data, and can be addressed as a future study. While the proposed routing algorithm can provide a reasonably performing, if not optimal, solution, investigating its theoretical properties as well as conducting a comparative study with other RPP solutions can provide more insights into the problem. Finally, a thorough study on determining the effective speed and the flight time of a drone based on extensive flight testing can be another venue for future study.

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APPENDIX-A: USER INSTRUCTIONS TO FIND DAMAGE ASSESSMENT PARAMETERS FROM DRONE ROUTING ALGORITHM

The MATLAB GUI application was developed for utility users to schedule damage assessment in conjunction with drone technology. Given a set of input data containing the topologies of circuits that experience outage, the application produces a spreadsheet, which consists of parameters input file name, root node, X and Y coordinates of root node, damage assessment time, total flight distance, battery replacement vertices, and drone path of each affected network. The application operates on Windows operating system. To run this application, a commercial solver, GUROBI, must be interfaced with MATLAB.

<u>Instruction Steps with Illustrative Example</u>

Step 1:

Open "*drone routing algorithm.m*" file from MATLAB. Run the program, it shows up a dialog, which asks for the number of circuits to be inspected. Figure A1 below shows an example screenshot of the GUI to input number of circuits.

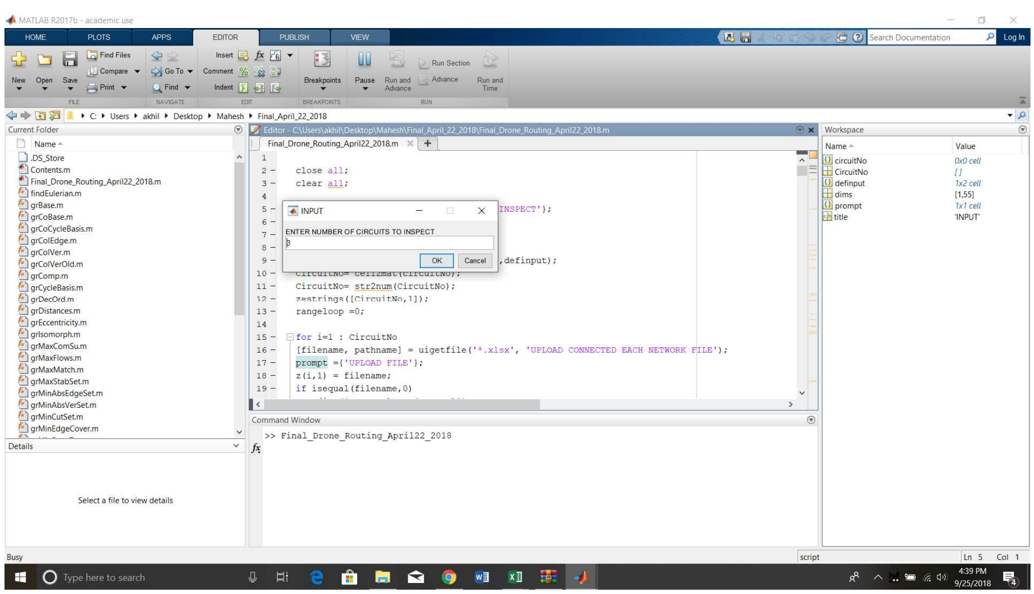
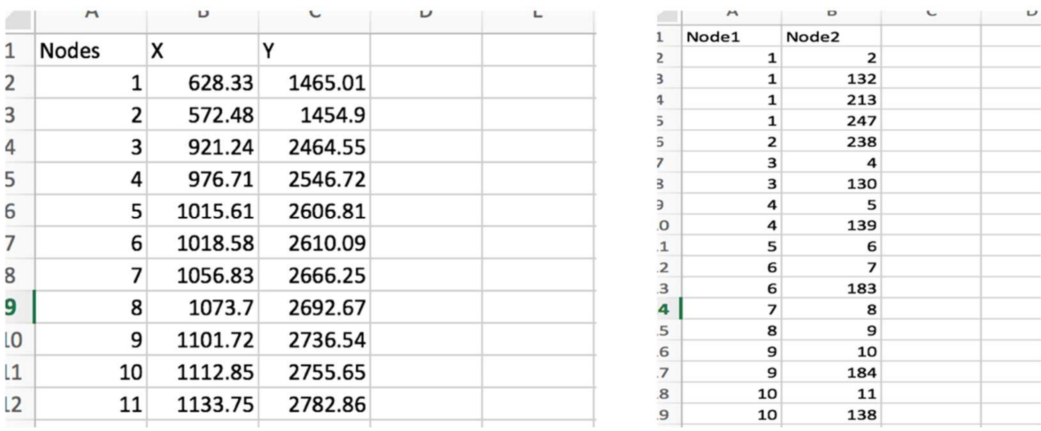


Figure A1: Input number of affected circuits*Step 2:*

Once the user inputs the number of circuits to inspect, it sequentially opens dialogs to read the given number of input files. Input file format is in Excel, where the first sheet contains information about vertices and their corresponding x and y coordinates. In the second sheet, the list of edges with associated vertices is provided. Figure A2 displays examples of the input file format of sheet 1 and sheet 2. Figure A3 shows window, which asks to upload files.



Nodes	X	Y
1	628.33	1465.01
2	572.48	1454.9
3	921.24	2464.55
4	976.71	2546.72
5	1015.61	2606.81
6	1018.58	2610.09
7	1056.83	2666.25
8	1073.7	2692.67
9	1101.72	2736.54
10	1112.85	2755.65
11	1133.75	2782.86

Node1	Node2
1	2
1	132
1	213
1	247
2	238
3	4
3	130
4	5
4	139
5	6
6	7
6	183
7	8
8	9
9	10
9	184
10	11
10	138

Figure A2: Input file format of sheet-1and sheet-2

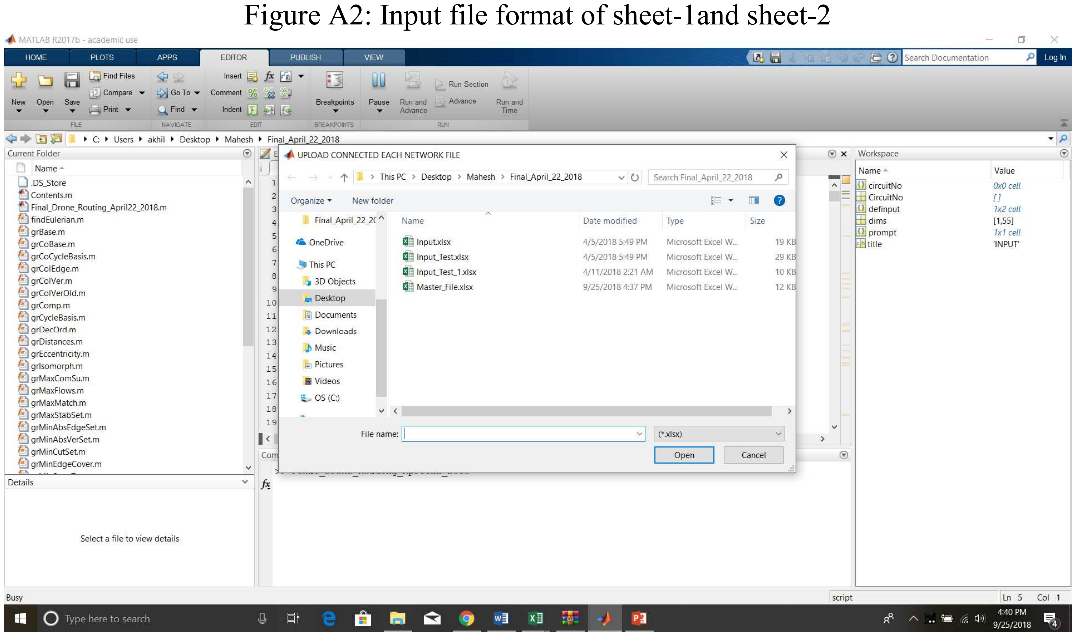


Figure A3: Upload topology data of affected networks in format as shown in Figure A2

Step 3:

After the user inputs data, application starts processing and provides a window as shown in Figure A4. Once successfully completed, the result will be written in a file named "Master_File.xlsx" in the same folder. Figure A5 shows an example screenshot of Master_File.xlsx.

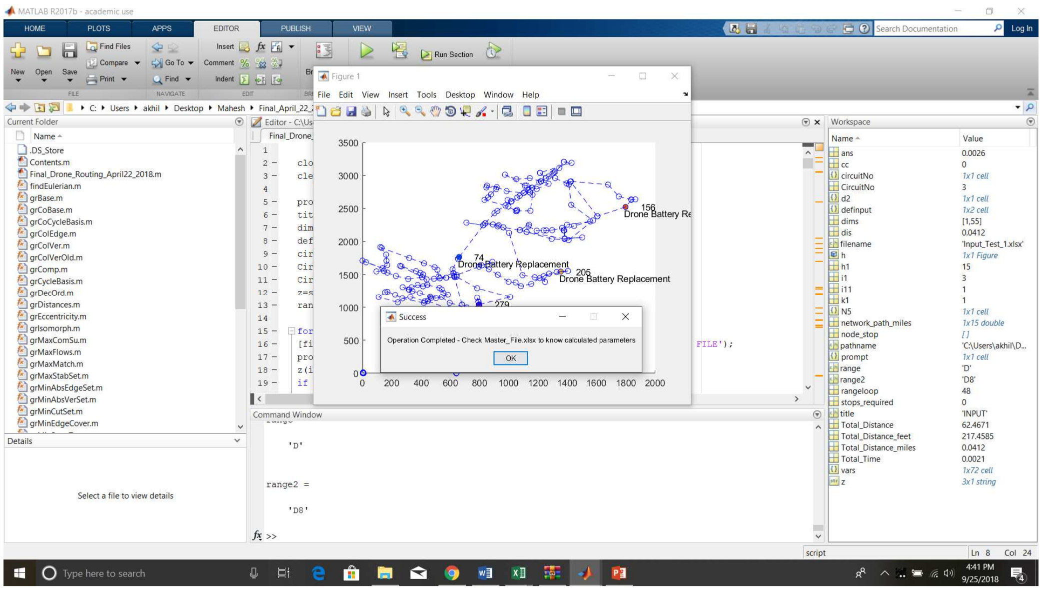


Figure A4: Completion of runs

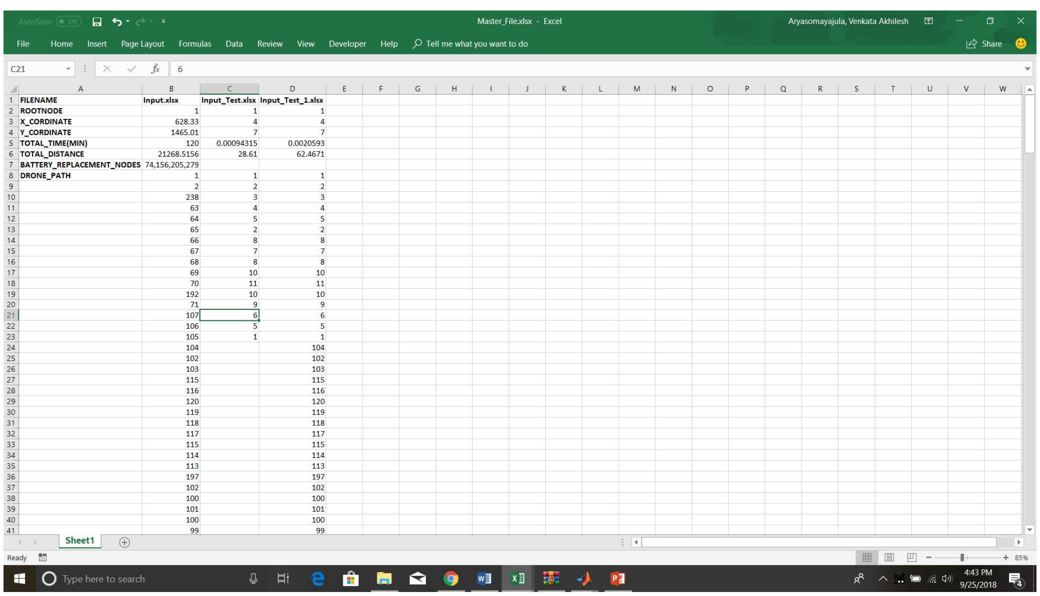


Figure A5: Screenshot of resulting solution example in xlsx file format

APPENDIX-B: USER INSTRUCTIONS TO FIND DAMAGE ASSESSMENT SEQUENCE OF MULTIPLE CIRCUITS

The MATLAB GUI application was developed for utility users to known damage assessment sequence of multiple circuits during power outage (Chapter 5). Additionally, it allows users to select either the modified LPT or the modified SPT based on utility requirement. Given a set of input data containing the damage assessment time of circuits, distances from the operation center to circuits and distances between circuits, the application produces makespan, total completion time and the sequence of circuits to be inspected. The application operates on Windows/MacOS operating systems.

<u>Instruction Steps with Illustrative Example</u>

Step 1:

Open "*damage_assessment_sequencing.m*" file from MATLAB. Run the program, and then it shows up a dialog, which asks for the number of damage assessors available for inspection. Figure B1 below shows an example screenshot of the GUI to input the number of damage assessors available.

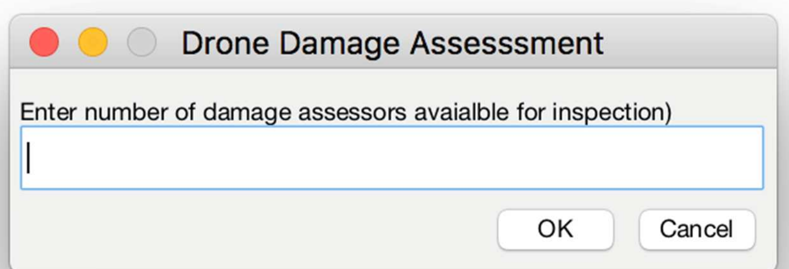


Figure B1: Screenshot of input dialog

Step 2:

Once the user inputs the number of damage assessors, it opens a dialog to read the given input file. Input file format is in Excel, where the first sheet contains information about damage assessment of each affected circuit in the first row and distances from the operation center to affected circuits in the second row. The second sheet contains distances from circuits to circuits. Figure B2 displays examples of the input file format of sheet 1 and sheet 2.

46	58	72	87	104
9	12	5	3	6

0	7	6	4	12
7	0	11	6	8
6	11	0	4	10
4	6	4	0	6
12	8	10	6	0

Figure B2: Example of input file format of sheet-1and sheet-2

Step 3:

When the user uploads input data, the application opens a dialog window, which asks the user to select either LPT or SPT as shown in Figure B3.

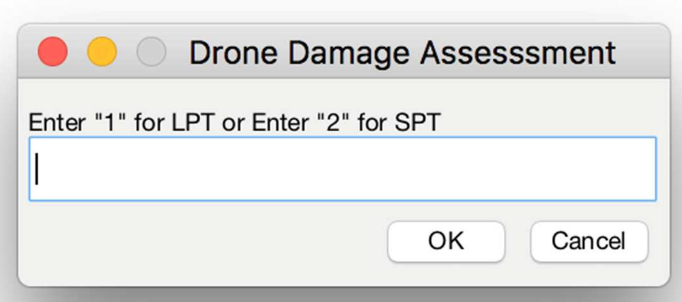


Figure B3: Screenshot of algorithm selection dialog

Step 4:

When the user selects LPT or SPT, application starts processing and produces results as shown in Figure B4. Once successfully completed, the result will be written in a file named “Damage_Assessment_Sequence.xlsx” in the same folder. Figure B5 shows an example screenshot of Damage_Assessment_Sequence.xlsx.

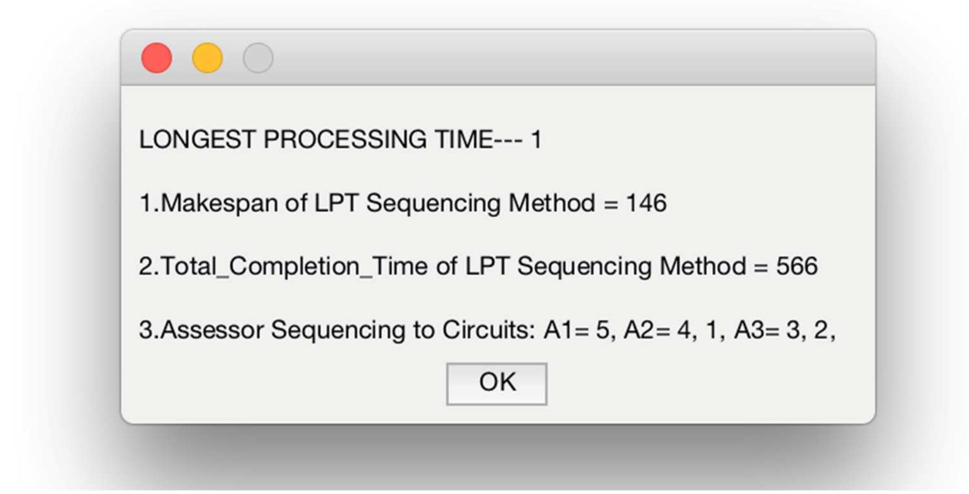


Figure B4: Screenshot of resulting solution example

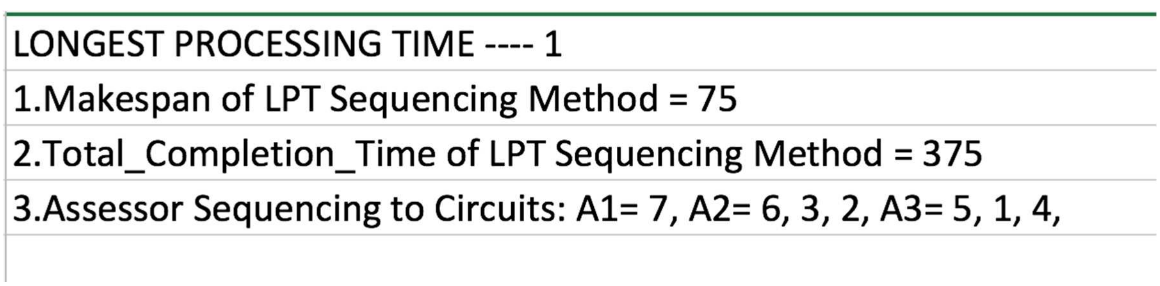


Figure B5: Screenshot of resulting solution example in xlsx file format