# A Heuristic Approach for On-line Signal Repair Problems

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**Abstract:** Due to the advancement of information and communication, city logistics operations could be designed more efficiently, especially for on-line requests. This research proposes an on-line algorithm to consider new requests and real-time traffic conditions for signal repair problems. The research framework includes two parts, off-line route planning and on-line route updating. The off-line problem is solved through a time-dependent mathematical formulation and the CPLEX solver. The on-line algorithm is constructed based on two heuristic approaches, the INTERVAL strategy and the Simulated Annealing (SA) algorithm. The INTERVAL strategy considers new demands at appropriate intervals, while the SA algorithm is applied to generate the best service route. Numerical experiments through the simulation-assignment model, DynaTAIWAN, are conducted to illustrate the algorithm. The results describe that positive benefit, about 13.4% of reduction in the total completion time, is achieved when comparing with empirical data in a real city network.

*Keywords:* Traveling Repairman Problems, Signal Repair Problems, INTERVAL Strategy, Simulated Annealing Algorithm

## 1. INTRODUCTION

Due to the advancement of information and communication, city logistics operations could be designed more efficiently, such as dynamic repair operations for on-line requests. These repair operations require efficient algorithms to re-schedule the repair routes in order to achieve minimum completion time. One of the common repair operations in an urban city is signal maintenance. Signal malfunction, especially after natural disasters, causes great impact on traffic systems in urban areas; therefore, how to design an efficient signal repairing plan is a critical issue to ensure traffic safety and efficiency.

The signal repair problems belong to a class of problems, traveling repairman problems (TRP). TRP focuses on constructing repair routes to minimize the total completion time. The completion time of a request is defined as the waiting time plus the service time of the request. TRP can be defined as follows: given a set of $n$ demand points and associated priorities, a repairman is dispatched to visit the demand points, with the goal minimizing the average weighted completion time or the total weighted completion time (Blum *et al*., 1994; Garcia *et al*., 2002; Sarubbi and Luna, 2007).

The research framework includes two main parts in the algorithm, off-line route generation and on-line route updating. In order to consider the variations of travel times in traffic networks, a time-dependent mathematical formulation is constructed to generate initial routes based on known demand information. The on-line algorithm is constructed based on two heuristic approaches, the INTERVAL strategy (Krunke, 2000) and the Simulated

Annealing (SA) algorithm (Kirkpatrick *et al*., 1983). The INTERVAL strategy provides the time intervals for the algorithm to review new requests and the SA algorithm generates the optimal repair route.

Numerical experiments in a real city network are conducted in a real city network to illustrate the algorithm. The experiments are evaluated in a realistic simulation environment to consider new requests as well as real-time traffic information. The simulation is achieved through the simulation-assignment model, DynaTAIWAN (Hu *et al*., 2007).

The major contributions of this study include: proposing a workable heuristic approach for on-line signal repair problems; providing an empirical analysis based on theoretical development; integrating different approaches to model on-line problems; illustrating possible benefits of the on-line algorithm through a real world case.

A brief review of TSP is presented in the next section. The proposed algorithms and associated modeling issues are described in Section 3. Experimental design and results are discussed in Sections 4 and 5, followed by concluding comments.

## 2. LITERATURE REVIEW

The traveling repairman problems and solution approaches are reviewed and the process of signal repair work in Taiwan is also described.

### 2.1 Traveling Repairman Problems and Solution Approaches

TRP, one of the important issues in Operations Research, is regarded as a variant of the famous traveling salesman problem (TSP) (Blum *et al*., 1994; Garcia *et al*., 2002). TRP is defined as follows (Krunke, 2000): Given a set of n demand points and the priority in a metric space, and a repairman should visit the points at unit velocity, defining the completion time $C_j$ ($j$ =1,…,$n$) of a point $p_j$ to be the length of the tour from the origin before he/she reaches $p_j$. Given weight $w_j$ ($j$ =1… $n$) for the point, the goal of TRP is to minimize the average weighted completion time or the total weighted completion time. TSP's objective is focused on the minimization of the salesman's travel time, but TRP's objective is closely related to the notion of latency, the average completion time of all demands, which keeps customers' interest in mind rather than server's one (Jaillet and Wagner, 2006).

The dynamic traveling repairman problems (DTRP) consider the dynamic version of this problem, such as demands or traffic information appear over time, and thus the repairman should have real-time policies for those new demands. Also, for the better route scheduling, the problem involves demands' queuing phenomena (Bertsimas and Ryzin, 1989).

Several approaches have been developed to solve DTRP or on-line TRP, including heuristics, meta-heuristics, and mathematical programming. Bertsimas and Ryzin (1989) proposed four policies to deal with DTRP under light and heavy traffic conditions, including FCFS policies, partitioning policies based on cyclic queues, TSP, and the nearest neighbor policy. Krumke (2000) described the INTERVAL strategy, online-scheduling for DTRP, which provides a simple method of getting time intervals, in order to determine what time the algorithm should accept new demands, schedule and serve them. Jaillet and Wagner (2006) introduced the notion of a request's disclosure date, the time when a city's location and release date are revealed to the server, which helps the INTERVAL strategy become more efficient.

SA is a meta-heuristic approach to deal with the combinatorial optimization problems, including TSP (Kirkpatrick, 1984; Herault, 2000; Schneider, 2002), MLP (YarKhan and

Dongarra, 2002), and vehicle routing problems (Chiang and Russell, 1996; Czech and Czarnas, 2002). The SA algorithm was first used by Kirkpatrick *et al*. (1983) to search the best possible solution in the annealing process for optimal problems, avoiding becoming trapped in local minima. Busetti (2009) highlighted several important characteristics of the SA algorithm, one of the important advantages of the SA algorithm is its flexibility and ability to approach global optimality; however, the major disadvantage is that there is a tradeoff between the quality of the solutions and the required time of computing.

Mathematical programming is also extensively applied to solve the combinatorial optimization problems, and the formulation for DTRP was constructed by Rocha *et al*. (2005) and Sarrubbi and Luna (2007).

## 2.2 Signal Repair Work in Practice

In the Kaohsiung City, the signal repair work is managed by the Transportation Management Center (TMC). The signal-related works include inspection and repair of traffic control devices, such as signal lights, traffic controller, Changeable Message Sign (CMS), and vehicle detectors. The repair process, as shown in Figure 1, is described as follows:

1) Identification of signal malfunction
   Several channels are used to identify signal malfunction. One of the channels is citizen’s reports, and the citizens can provide the information about signal malfunctions, including time, place and type of malfunction, etc.
2) Route scheduling
   TMC artificially schedules the repairman route according to previous experiences.
3) Schedule new requests and re-route planning
   When new demands are reported during repair process, the center would call the repairmen and insert the new demands into the original routes. The insertion is determined by the importance of the signal.
4) Routine inspection
   If there is no request in the beginning of the daily work, the repairman performs routine inspection.

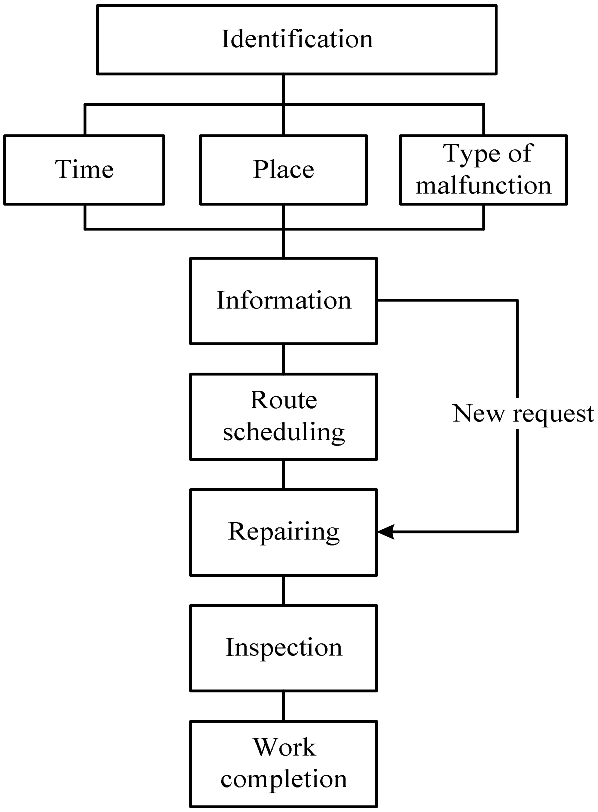


Figure 1. Signal repair process in the Kaohsiung city

## 3. RESEARCH FRAMEWORK AND SOLUTION ALGORITHMS

The research framework and the proposed algorithms, including the time-dependent formulation, the INTERVAL strategy and the SA algorithm, are described and discussed.

### 3.1 Research Framework

The conceptual framework is shown in Figure 2. There are two major parts, off-line route planning and on-line route updating. The off-line planning algorithm designs initial service routes and the on-line route updating part redesigns new routes with the considerations of new requests and new traffic conditions. The off-line problem is solved through a time-dependent mathematical formulation and the CPLEX solver. The on-line algorithm considers new requests as well as dynamic traffic conditions and the objective function is to minimize the total weighted completion time, $\Sigma w_i C_i$ , where $w_i$ is the weight of demand and $C_i$ is the completion time of each demand.

The on-line algorithm acquires information of known demands and generates initial route of service from a time-dependent formulation and then re-schedules the route based on on-line requests. The route provides the sequence of service for the repairmen and the travel cost is the sum of travel time. In order to estimate the performance of the on-line algorithm, the on-line solution is compared with the off-line result computed by the time-depend formulation. The generated routes are evaluated through the simulation-assignment model, DynaTAIWAN (Hu *et al.*, 2007), and the route travel time is simulated based on the route.

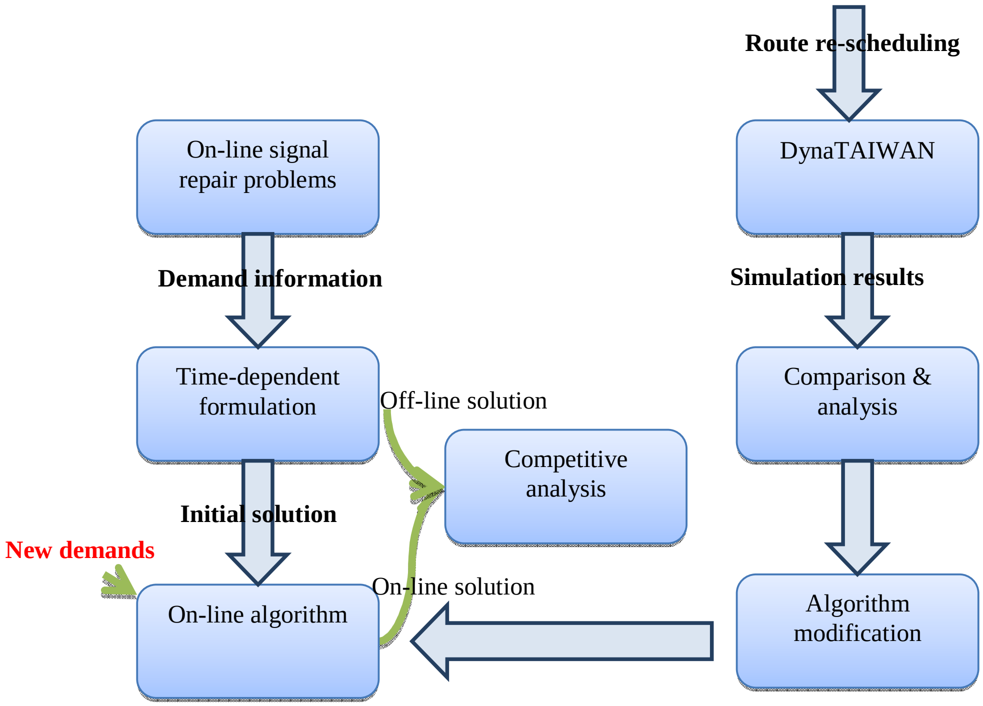


Figure 2. Research framework for the on-line signal repair problems

Basic assumptions are summarized as follows:

1) There is only one management center and each repairman starts from and returns to the center.
2) The weight $w_i$, $w_i \in \{1,2,..,10\}$ depends on the importance of the intersections.
3) The average service time of actual signal repair work is used in this study to represent the service time for signal repair work.
4) Once the on-line information is released, repairmen can change the route at the next intersection.

### 3. 2 Time-Dependent Formulation

The idea proposed by Malandraki and Daskin (1992) is adopted to reflect time-dependent travel times. The time-dependent formulation for signal repair problems is constructed and the travel cost is represented by step function. Thus link travel time for each time interval can be defined to reflect traffic peak congestion.

The formulation is summarized as follows:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{m=1}^{M} w_j c_{ij}^m g_{ij}^m \qquad (i \neq j) \tag{1}$$

subject to

$$\sum_{i=1}^{n} \sum_{m=1}^{M} x_{ij}^m = 1 \qquad (j = 1,2,..., \text{n}; i \neq j) \tag{2}$$

$$\sum_{j=1}^{n}\sum_{m=1}^{M} x_{ij}^{m} = 1 \qquad (i = 1,2,..., \mathrm{n}; i \neq j) \tag{3}$$

$$t_j - t_i - Dx_{ij}^{m} \geq c_{ij}^{m} - D \tag{4}$$

$$t_j - t_i + Dx_{ij}^{m} \leq c_{ij}^{m} + D \tag{5}$$

$$t_i - T_{ij}^{m-1} x_{ij}^{m} \geq 0 \tag{6}$$

$$t_i + Dx_{ij}^{m} \leq T_{ij}^{m} + D \tag{7}$$

$$\sum_{j=2}^{n} g_{1j}^{m} = n \tag{8}$$

$$g_{ij} = \sum_{m=1}^{M} g_{ij}^{m} \, (i, j = 1,..., n; i \neq j) \tag{9}$$

$$g_{ik} - g_{kj} = 1 \;\; (i, j = 1,..., n; k = 1,..., n; i \neq j \neq k) \tag{10}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n} g_{ij} = 1 + 2 + \cdots + n \tag{11}$$

$$g_{ij}^{m} \leq nx_{ij}^{m} \quad (i, j = 1,..., n; i \neq j; m = 1,..., M) \tag{12}$$

$$g_{ij}^{m} \geq 0 \;\; (i, j = 1,..., n; i \neq j; m = 1,..., M) \tag{13}$$

$$x_{ij}^{m} \in \{0,1\}; g_{ij}^{m} \in \text{integer} \quad (i, j = 1,..., n; m = 1,..., M) \tag{14}$$

where

$n$ : total number of nodes, $i$=1 represents the repair center, and there are $n$-1 repair requests,

$m$ : time interval for travel cost, $m$=1…$M$,

$c_{ij}^{m}$ : the travel cost from node $i$ to node $j$ at time interval $m$, including link travel time from node $i$ to node $j$ and the repair time at node $j$,

$T_{ij}^{m}$ : the upper bound of travel time from node $i$ to node $j$ at time interval $m$,

$D$ : a big real number,

$w_j$ : weight for demand node $j$.

Decision variables:

$$x_{ij}^{m} = \begin{cases} 1, & \text{the repair vehicle move from } i \text{ to } j \text{ at time interval } m \\ 0, & \text{otherwise} \end{cases}$$

$g_{ij}^{m}$ : the cumulative flows from node *i* to node *j* at time interval *m*,

$t_i$ : the departure time from node *i*,

$g_{ij}$ : the cumulative flows from node *i* to node *j*.

The completion time and weight for each signal are represented by $C_i$ and $w_i$, respectively. The total weighted completion time is $\sum w_i C_i$ , as proposed by Krumke (2000) and Jaillet and Wagner (2006). However, the objective function is reformulated and represented by link cost and cumulative flows, as suggested by Sarubbi and Luna (2007).

Equation (1) is the objective function and minimizes total completion times. Equations (2) and (3) ensure that each demand must be visited exactly once and each demand is allowed to be served by one repair team. Equations (4) and (5) define departure time on node *j*. If a link *x(i,j)* is used, then $t_j - t_i = c_{ij}^{m}$ . If a link *x(i,j)* is not used, $t_i$ and $t_j$ are not related. Equation (6) and (7) are the constraints for travel time departing from node *i* at time interval *m*. $g_{ij}$ is the cumulative flows from node *i* to node *j* and vehicles passing link *(i,j)* represent a service is fulfilled. Thus, equations (8), (9) and (10) are used to describe $g_{ij}$ . Equation (8) states the flow leaving the depot is equal to the number of signal node to be visited. Equation (9) represents the balance equation of the cumulative link flows. Equation (10) states that the cumulative flows are decreasing after visiting each node, and Equation (11) represents the summation of total cumulative flows. Equations (10) and (11) are defined to avoid sub-tours. Equation (12) states that cumulative flows only exist for passing links. Equations (13) and (14) are non-negativity and integer conditions.

### 3.3 The INTERVAL Strategy

As an element of the on-line algorithm to update coming requests in real time intervals, the INERVAL strategy provides flexibility to construct the on-line strategy for the new coming requests in each interval. The strategy updates demand requests at the starting time of intervals and computes a schedule for the non-scheduled requests. The steps of INTERVAL process are described as follows:

Step 1. Initialization:

Input the known demands and define the initial values of latency (*L*) in order to determine the length of time intervals.

1) If there is no request at time 0, repairmen wait until the requests released at time $t_1$, and set $L: = t_1$.
2) If requests released at time 0, compute the route for known requests by the SA process, with minimum travel time *T*, and set $L: = T$.
3) If there is no more new request before time *T*, set $L: = T$. Otherwise, if requests are released at time t ($0<t< T$), set $L: = t$.

Step 2. Time intervals

After the initialization, the *i*th interval phase starts at time $B_i$, where $B_i: =\alpha^{i-1}L$ (*i*=1, 2…). New requests released after $B_i$ are reviewed and inserted to the original route by the SA process.

### 3.4 The Simulated Annealing Algorithm

The SA algorithm, introduced by Metropolis *et al*. (1953), is a meta-heuristic algorithm that can be used to provide an efficient simulation of a collection of atoms in equilibrium at a given temperature, and the temperature would change by a cooling process. Kirkpatrick *et al.* (1983) suggested that the method can be used to search the feasible solution converging to an optimal solution. Notations in the SA algorithm are defined in Table 1; there are temperature and iteration factors.

Table 1. Notations of SA process

| | | | |
|---|---|---|---|
| $T$ | Initial temperature | $N_{max}$ | Maximal iteration |
| $t$ | Current temperature | $n$ | Number of demands |
| $N$ | Recent iteration | | |

The process of SA in the on-line algorithm is shown in Figure 3 and algorithm steps are summarized as follows:

Step 0. Initialization

Input the data of demands and parameters $T$ and $N_{max}$, and randomly generate an initial solution.

Step 1. Local optimization

The 3-opt method (Lin, 1965) is applied to find feasible solutions. If the result is better, the current optimal solution is replaced by the feasible solution.

Step 2. Acceptance function

Calculate $\delta C$ between the new solution and the recent best solution. If $\delta C < 0$, the new solution replaces the current best one; otherwise the probability of acceptance is calculated by acceptance function:

$$p(\delta C) = \exp(-\delta C / \kappa t) \tag{15}$$

Where $p(\delta C)$ denotes the probability of acceptance of the inferior solution with increasing cost, $t$ is the temperature, and $\kappa$ is the Bolzmann's constant. When the temperature decreases over time, the $p(\delta C)$ would decrease. If the process accepts the inferior solution, then return to step 2.

Step 3. Annealing scheduling

When the current best solution is renewed, the temperature will decrease by $T(t)$ and the iteration will be increased by 1 until the iteration = $N_{max}$.

Step 4. Stopping criterion

If the iteration = $N_{max}$, the process stops and the best solution is set to the current best solution.

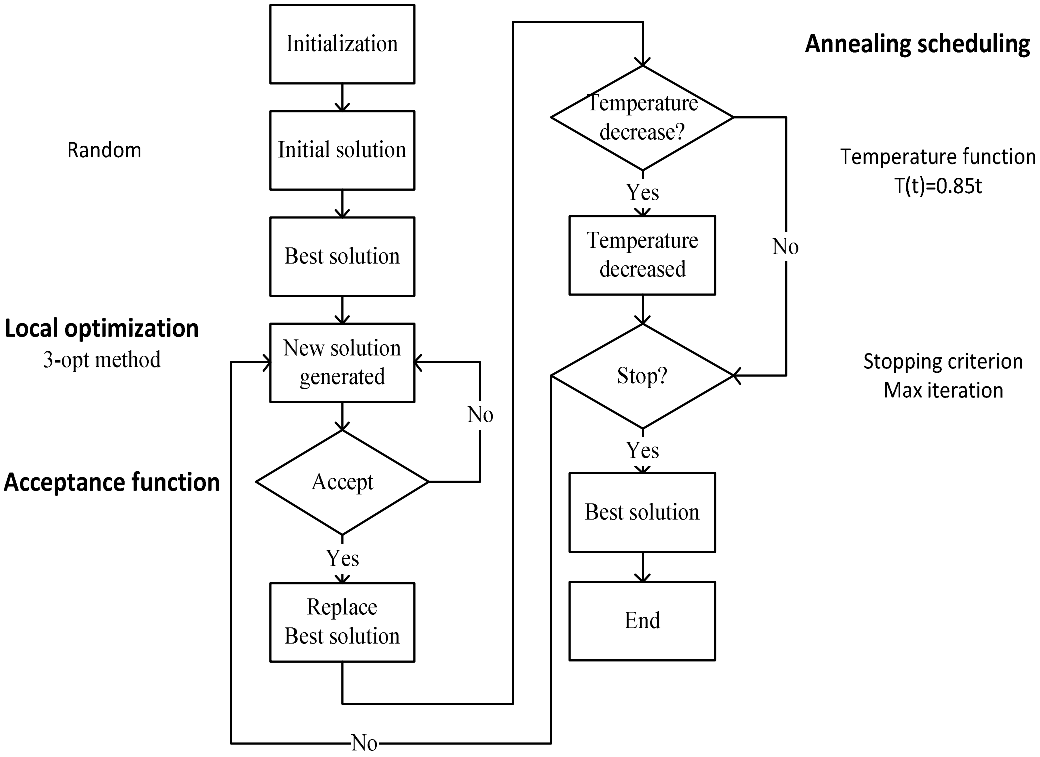


Figure 3. The Simulated Annealing algorithm

## 4. NUMERICAL EXPERIMENTS

The numerical experiments and empirical data based on the Kaohsiung City sub-network are conducted to illustrate the proposed algorithms.

### 4.1 Data Collection and Description

Field data is collected from the TMC, Kaohsiung City, during September, 2008. The Kaohsiung City sub-network includes 27 zones, 132 nodes and 363 arcs, as shown in Figure 4. The traffic flow is generated from the time-dependent O-D demand matrix, including passenger cars, trucks, and motorbikes.

The average number of signals' malfunction is 12.9 per day after the typhoon. The official worksheet of signal repair work is illustrated in Table 2. The signal repair work in the Kaohsiung City is a zone-based system, which means that each repair team is assigned to a specific zone and the team is responsible for maintaining signal operations in this zone. The signal repair works include inspection and repair of traffic control devices, such as signal lights, traffic controller, CMS, and vehicle detectors.

The detailed information from empirical data, including released time, finished time, completion time and sequence of service, are shown in Table 3. The geometric locations of demand nodes are illustrated in Figure 4. The completion time is calculated by finished time minus released time. For example, the released time of demand node 4 is 09:15 AM, the finished time is 14:40PM, and the completion time is 325 minutes. The total completion time, the summation of all completion time, is 759 minutes and the average completion time for each demand node is about 76 minutes. From Table 3, it is obvious that the schedule of the repair team is very busy and they were traveling in the city and trying to fix every control device on time. The objective of the proposed algorithms is to re-arrange the schedule and minimize the total completion time when there are on-line requests.

Table 2. Signal repair worksheet in the Kaohsiung City

Traffic facility repair and service management

Traffic facility repair record

North-1 Area (1st shift) September 29, 2008

Recorder A Repairmen B, C

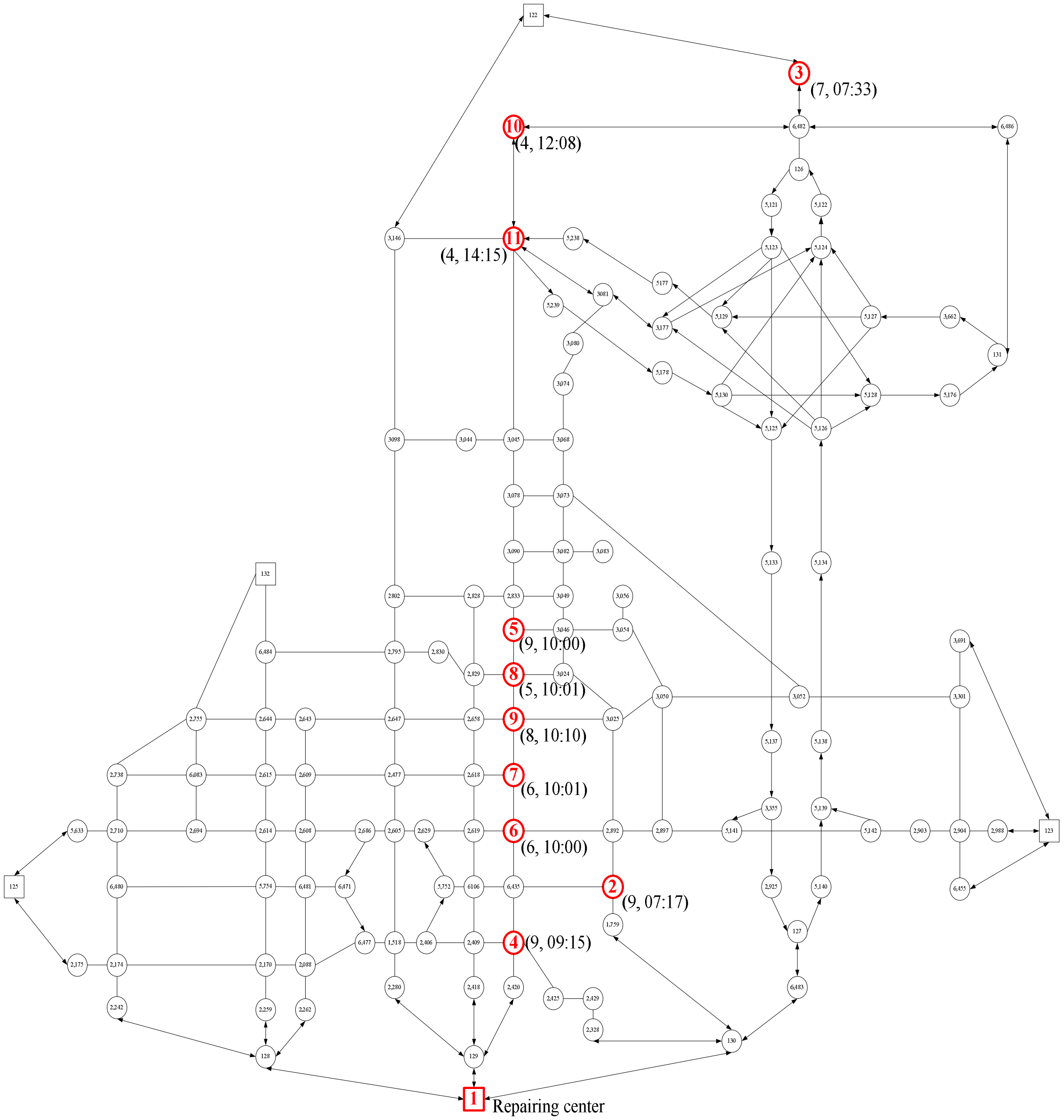
| No. | Reporter | Time | Place | Contents | Repairmen | Finished time | Result |
|---|---|---|---|---|---|---|---|
| **1** | Center | 07:00 | CMS/PGIS inspection | CMS inspection | Chung-Ming Wu, Chung-Yi Lin | 07:30 | OK |
| **2** | Inhabitants | 07:17 | Jianguo - Kaixuan Rd. | signal lights don't work | Chung-Ming Wu, Chung-Yi Lin | 07:45 | run short of electricity |

Completion time(min), Type, Weather, Weekday/Holiday, Peak/Off-peak hour, Main/ Branch Lane, Other repairs doing, Repairmen’s current site, Motor/Car, Able to repair (Y/N), Self-inspect (Y/N)

(Source: The Transportation Management Center, Transportation Bureau, Kaohsiung City, 2009)

Table 3. Repairing route in the field data

| Node number | Released time | Finished time | Sequence of service | Completion time |
|---|---|---|---|---|
| 1 | -- | -- | 0 | -- |
| 2 | 07:17 | 07:45 | 1 | 28 |
| 3 | 07:33 | 09:35 | 2 | 122 |
| 4 | 09:15 | **14:40** | 10 | 325 |
| 5 | 10:00 | 10:05 | 3 | 5 |
| 6 | 10:01 | 10:35 | 5 | 34 |
| 7 | 10:01 | 10:50 | 6 | 49 |
| 8 | 10:01 | 11:00 | 7 | 59 |
| 9 | 10:10 | 10:20 | 4 | 10 |
| 10 | 12:08 | 14:10 | 8 | 122 |
| 11 | 14:15 | 14:20 | 9 | 5 |
| Route | 1-2-3-5-9-6-7-8-10-11-4 | | | 759 |



②-⑪ : Signals to be repaired
(9, 09:15): (weight, released time)
1: Repairing center

Figure 4. Demand nodes in the Kaohsiung City sub-network

## 4.2 Experimental Setups

Two factors, weights of demand nodes and number of on-line demands, are tested in the numerical experiments. In these experiments, the repair work starts at 07:00 AM from the repairing center (node 1) and only one repair team for each zone is assumed. The maintenance time for each signal is assumed to be 13 minutes, which is the average value of each repairing work from field data. With the field data, the variations of service times could be easily added in the experiment. However, this study aims to provide a detailed analysis of the proposed algorithms.

The repair vehicles are simulated in a realistic simulation environment, DynaTAIWAN, and the vehicle trajectory is used to calculate the completion time and finished time for each demand node. Other vehicles are treated as background traffic with an origin-destination pair and assigned paths.

In practice, real-time can be observed through surveillance systems, such as AVI etc. In numerical experiments, DynaTAIWAN is also applied to obtain time-dependent traffic conditions and link travel times. The experimental setups are summarized in Table 4 and the detailed descriptions are given below.

Table 4. Experimental setups

| Experiment | Weights of demand nodes | Number of demands known in advance | Number of on-line demands |
|---|---|---|---|
| I | 1 | 10 | 0 |
| II-2 | 1 | 8 | 2 |
| II-4 |  | 6 | 4 |
| II-6 |  | 4 | 6 |
| II-8 |  | 2 | 8 |
| II-10 |  | 0 | 10 |
| III | 5~10 | 0 | 10 |

1) Experiment I
   The experiment I, as the basic experiment, provides off-line results for the signal repair problem. In this experiment, signals to be repaired are assumed to be known in advance and equal weights are given to demand nodes.
2) Experiment II
   New requests are assumed to be released while the repairmen are en-route. There are 5 experiments, II-2, II-4, II-6, II-8, and II-10, and the numbers of new requests are 2, 4, 6, 8 and 10, respectively. Thus, new routes are developed on-line based on the INTERVAL strategy and the SA algorithm.
3) Experiment III
   Different weights are defined according to the importance of the intersection, from 4 to 10, and the relationship between weights and components of the intersection is explained in Table 5.

Table 5. Definition of weights

| Weights | Road characteristics |
|---|---|
| 10 | interchange and major arterial |
| 9 | major arterial and major arterial |
| 8 | major arterial and minor arterial |
| 7 | minor arterial and minor arterial |
| 6 | major arterial and street lane |
| 5 | minor arterial and street lane |
| 4 | street lane and street lane |

### 4.3 Result Analysis

The numerical results, including weights, released time, sequence of repairs, finished time, and completion time, are presented.

1) Experiment I

Malfunctioned control devices are assumed to be known in advance at starting time 07:00 AM. The service route is generated through the time-dependent formulation of signal repairing problems.

The results are summarized in Table 6. The finished time for the last node, node 3, is 09:31 AM, and it takes 151 minutes to finish all repair works. The total completion time of all demands is 823 minutes, and it is about 82.3 minutes for each demand node. The repair route is 1-4-6-9-2-7-8-5-11-10-3.

The results show that the time to finish all the work is about 151 minutes and the average for each demand node is about 15 minutes. However, the average completion time is about 82.3 minutes for each demand node. Although the route could be arranged efficiently with known demands in advance, the completion time also increases due to the earlier released time.

Table 6. Results for the Experiment I (known demands + equal weights)

| Node number | Released time | Finished time | Sequence of service | Completion time |
|---|---|---|---|---|
| 1 | -- | -- | -- | 0 |
| 2 | 07:00 | 07:59 | 4 | 59 |
| 3 | 07:00 | **09:31** | 10 | 151 |
| 4 | 07:00 | 07:16 | 1 | 16 |
| 5 | 07:00 | 08:44 | 7 | 104 |
| 6 | 07:00 | 07:29 | 2 | 29 |
| 7 | 07:00 | 08:15 | 5 | 75 |
| 8 | 07:00 | 08:31 | 6 | 91 |
| 9 | 07:00 | 07:43 | 3 | 43 |
| 10 | 07:00 | 09:15 | 9 | 135 |
| 11 | 07:00 | 09:00 | 8 | 120 |
| Route | 1-4-6-9-2-7-8-5-11-10-3 | | | 823 |

2) Experiment II

With on-line requests, the review time interval is an important factor in the INTERVAL strategy. If the review time interval is too long, the on-line requests have to be hold before being considered in the service. On the contrary, if the time interval is too short, there might be too many route changes. In order to explore the appropriate time interval setting, the review time intervals, $\alpha$=1.5, 2.0, 2.5, and 3.0, are used in $B_i$: $=\alpha^{i-1}L$.

The variations of improvement with respect to the percentage of on-line demand nodes are illustrated in Figure 5. From both the variations of finished time and completion time, the results with $\alpha$=1.5 provide better performance and the variations are relatively stable. Thus, the time interval $B_i=1.5^{i-1}L$ is used in the rest of the experiments.

With different percentages of on-line demands, the results of Experiment II are summarized in Table 7, including repairing route and total completion time. The total completion time is not comparable between these experiments because each case has different input data. The field data can only be compared with the case II-10. With the proposed algorithms, the completion time reduces from 759 minutes to 657 minutes, a reduction of 13.4 %.

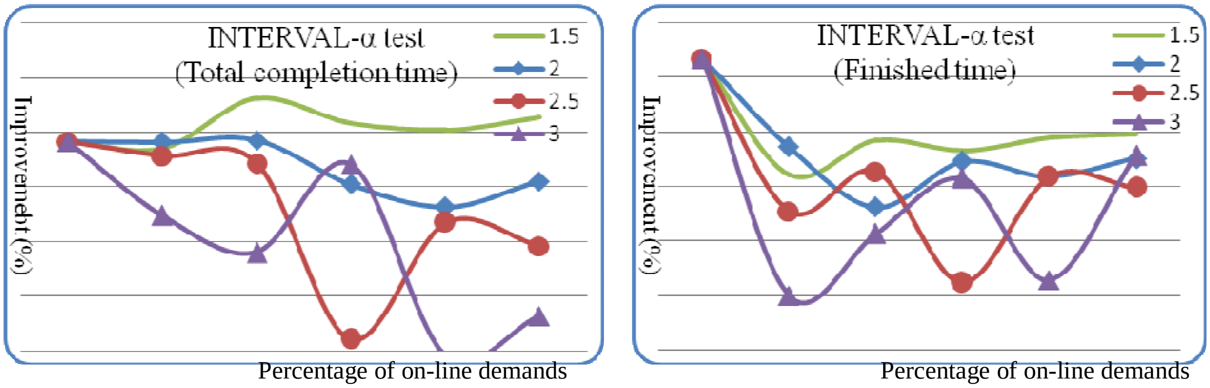


Figure 5. Sensitivity test for *α* in the INTERVAL strategy

Table 7. Results for the Experiment II (known demands + on-line demands)

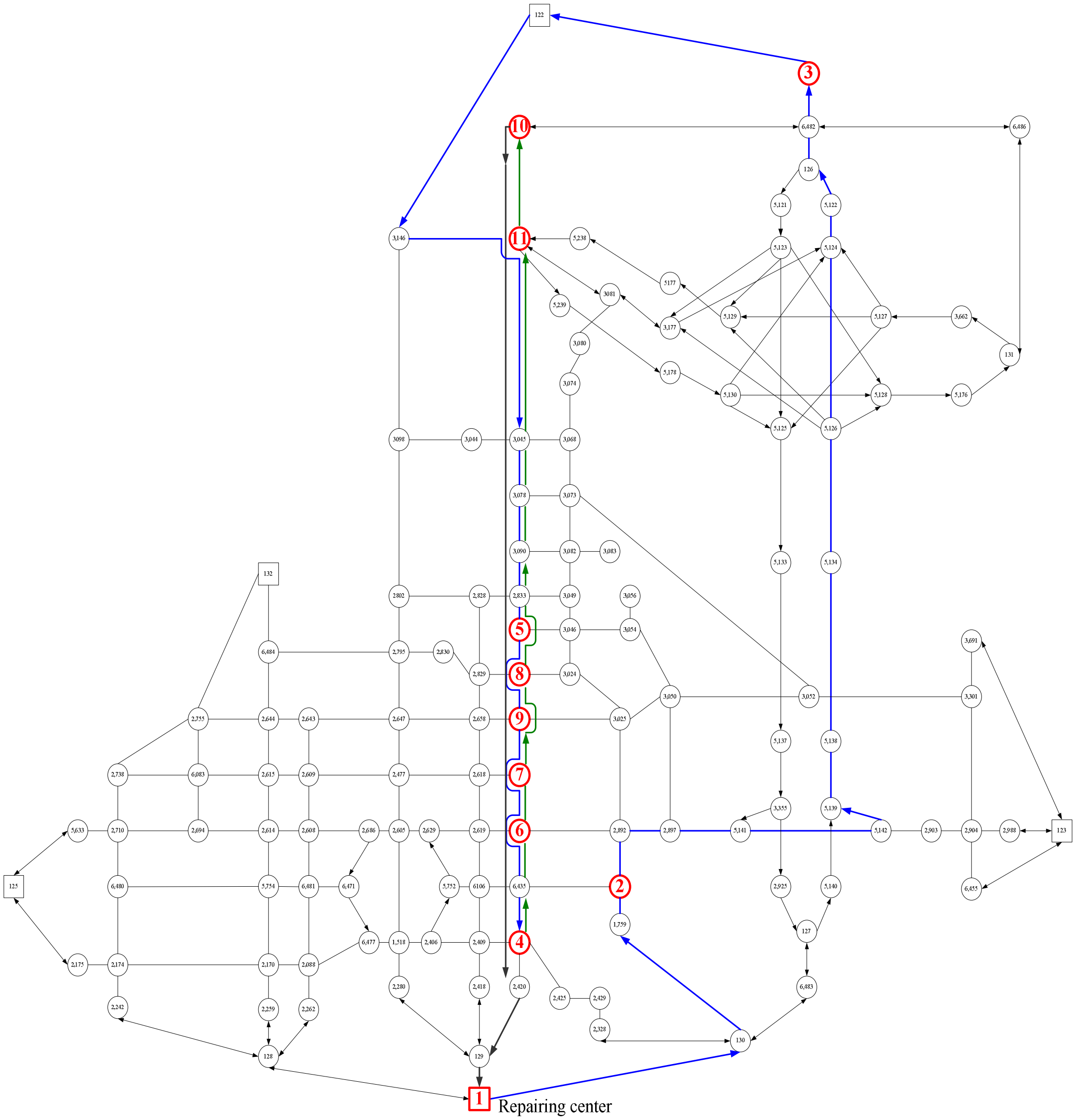
| | Field data | Experiments | | | | |
|---|---|---|---|---|---|---|
| | | II-2 | II-4 | II-6 | II-8 | II-10 |
| On-line demands (demand #) | 2,3,4,5,6,7, 8,9,10, 11 | 10,11 | 8,9,10, 11 | 6,7,8,9, 10,11 | 4,5,6,7,8 ,9,10,11 | 2,3,4,5,6,7, 8,9,10, 11 |
| Percentage of on-line demands | -- | 20% | 40% | 60% | 80% | 100% |
| Route | 1-2-3-5-9-6-7-8-10-11-4 | 1-2-6-9-7-4-8-5-3-10-11 | 1-2-6-4-7-5-3-8-9-10-11 | 1-2-4-5-3-8-9-7-6-10-11 | 1-2-3-5-8-9-7-6-4-11-10 | 1-2-3-5-8-9-7-6-4-11-10 |
| Total completion time (min) | 759 | 869 | 523 | 695 | 743 | 657 |

3) Experiment III

The results of Experiment III (10 on-line demands and different weights) are summarized in Table 8 and Figure 6. The repair route is 1-2-3-5-9-4-6-7-8-11-10. With the proposed algorithm, the completion time reduces from 759 minutes to 660 minutes, a reduction of 13 %.

Table 8. Results of the Experiment III (10 on-line demands + different weights)

| Node number | Weights | Released time | Finished time | Sequence of service | Completion time |
|---|---|---|---|---|---|
| 1 | -- | -- | -- | 0 | -- |
| 2 | 9 | 07:17 | 07:34 | 1 | 17 |
| 3 | 7 | 07:33 | 08:00 | 2 | 27 |
| 4 | 9 | 09:15 | 11:02 | 5 | 107 |
| 5 | 9 | 10:00 | 10:33 | 3 | 33 |
| 6 | 6 | 10:01 | 11:15 | 6 | 74 |
| 7 | 6 | 10:01 | 11:29 | 7 | 88 |
| 8 | 5 | 10:01 | 11:43 | 8 | 102 |
| 9 | 8 | 10:10 | 10:48 | 4 | 38 |
| 10 | 4 | 12:08 | **14:46** | 10 | 158 |
| 11 | 4 | 14:15 | 14:31 | 9 | 16 |
| Route | 1-2-3-5-9-4-6-7-8-11-10 | | | | 660 |



②-⑪ : Signals to be repaired
(9, 09:15): (weight, released time)
1: Repairing center

Figure 6. Repair route sequence in the Experiment III

### 4.4 Overall Discussion

With the same distribution of demands, the comparisons between on-line results (Experiment II-10 and III) and actual data, including route, total completion time and weighted completion time, are summarized in Table 9. The on-line results have smaller completion times than those of field data and the improvement is about 13.4%.

The Experiment III illustrates significant improvement on weighted completion time. The results indicate that the proposed algorithms with the consideration of demand weights efficiently improves the completion time with 25.2% in on-line problems.

When there are different weights between demands, requests with higher weights are served earlier as expected.

Table 9. Comparison between the experiments (repairing sequence)

| | | Field data | Experiment II-10 (on-line demands + equal weights) | Experiment III (on-line demands + different weights) |
|---|---|---|---|---|
| Route | | 1-2-3-5-9-6-7-8-10-11-4 | 1-2-3-5-8-9-7-6-4-11-10 | 1-2-3-5-9-4-6-7-8-11-10 |
| Completion time | Total value (minutes) | 759 | 657 | - |
| | Improvement (%) | - | 13.4 | - |
| Weighted completion time | Total value (minutes) | 5457 | - | 4084 |
| | Improvement (%) | | - | 25.2 |

## 5. PERFORMANCE EVALUATION: COMPETITIVE RATIO

Most studies use competitive analysis to evaluate the performance of on-line algorithms. The competitive ratio (Jaillet and Wagner, 2006) is defined as follows: assume a problem P is an on-line problem and A is an on-line algorithm for the problem P. $\mathrm{Cost}_{\mathrm{optimal}}(\mathrm{I})$ represents the off-line optimal result for the offline version of problem P and $\mathrm{Cost}_{\mathrm{online}}(\mathrm{I})$ is defined as the on-line results for the on-line problem P. The algorithm A is defined as r-competitive if the following condition holds:

$$\mathrm{Cost}_{\mathrm{online}}(\mathrm{I}) \leqq r\,\mathrm{Cost}_{\mathrm{optimal}}(\mathrm{I})\text{ , for all problem instances I} \tag{16}$$

Due to the complexity of the proposed algorithms, the competitive ratio for each individual instance is numerically calculated. The off-line version of the problem is represented as no on-line request case. The computational results are re-represented as competitive ratio, as shown in Table 10. The values of the ratio are within 2.914 and 4.238. If the worst case scenario is considered, the competitive ratio of the on-line algorithm is 4.238.

The theoretical competitive ratio from previous studies is summarized in Table 11. The theoretical results are classified into deterministic and stochastic on-line requests. The results in this study are better in deterministic cases, but not in the stochastic cases.

Table 10. Values of competitive ratio

| Weights | | | | Ratio of on-line requests | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 0% | 20% | 40% | 60% | 80% | 100% |
| Number of demand nodes | 5 | 1 | Completion time (minutes) | 80 | 269 | 254 | 268 | 287 | 262 |
| | | | Competitive ratio | (--) | 3.363 | 3.175 | 3.350 | 3.588 | 3.275 |
| | | 1~10 | Completion time (minutes) | 81 | 236 | 270 | 268 | 287 | 263 |
| | | | Competitive ratio | (--) | 2.914 | 3.333 | 3.309 | 3.543 | 3.247 |
| | 10 | 1 | Completion time (minutes) | 151 | 640 | 497 | 540 | 484 | 468 |
| | | | Competitive ratio | (--) | 4.238 | 3.291 | 3.576 | 3.205 | 3.099 |
| | | 1~10 | Completion time (minutes) | 158 | 660 | 497 | 540 | 481 | 466 |
| | | | Competitive ratio | (--) | 4.177 | 3.146 | 3.418 | 3.044 | 2.949 |

Table 11. Competitive ratio of the TRP algorithms

| Type of algorithm | On-line TRP | Upper bound | Lower bound |
|---|---|---|---|
| Deterministic | The proposed algorithm | 4.238 | 2.914 |
| | Jaillet and Wagner (2006) | $(1+\sqrt{2})^2 - \alpha\beta/(\alpha+\beta)$ | -- |
| | Krumke *et al*. (2003) | $(1+\sqrt{2})^2$<br>(~5.828) | -- |
| | Krumke (2000) | 8 | -- |
| | Feuerstein and Stougie (2001) | 9 | $1+\sqrt{2}$<br>(~2.414) |
| Stochastic | Jaillet and Wagner (2006) | $4/\ln 3 - \alpha\beta/(\alpha+\beta)$ | -- |
| | Krumke *et al*. (2003) | 4/ln3<br>(~3.6410) | 7/3<br>(~2.333) |
| | Krumke (2000) | 4/ln2<br>(~5.7708) | -- |

$\alpha = a / L_{TSP}$ , $\beta = a / r_{\max}$ ; a= release date ( $r_i$ ) - disclosure date.

## 6. CONCLUSIONS

This research aims at providing efficient routing and scheduling for signal repairing work by proposing the time-dependent formulation and the on-line algorithm. The INTERVAL strategy processes on-line request and the SA algorithm re-sequences all requests to minimize weighted completion time.

Numerical experiments are conducted to illustrate the algorithms and empirical data is compared with the results from different scenarios. The results show that the improvement in terms of the total completion time is about 13.4% and the improvement in terms of the total weighted completion time is about 25.2% in on-line problems. Thus, the proposed algorithms can efficiently optimize signal repair routes based on given information, such as new requests or weights of demands. The proposed algorithms show its applicability in finding efficient sequence and routes for signal repair work.

Although the theoretical competitive ratio is unable to be proved in this study, numerical values of competitive ratio are computed. The values of the ratio are within 2.914 and 4.238 and the results are promising when comparing with the previous studies.

However, the results also indicate that the on-line algorithm cannot minimize both the finished time and the completion time of signal repairing work. The trade-off between the finished time and the completion time needs to be carefully balanced by the operator.

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