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.

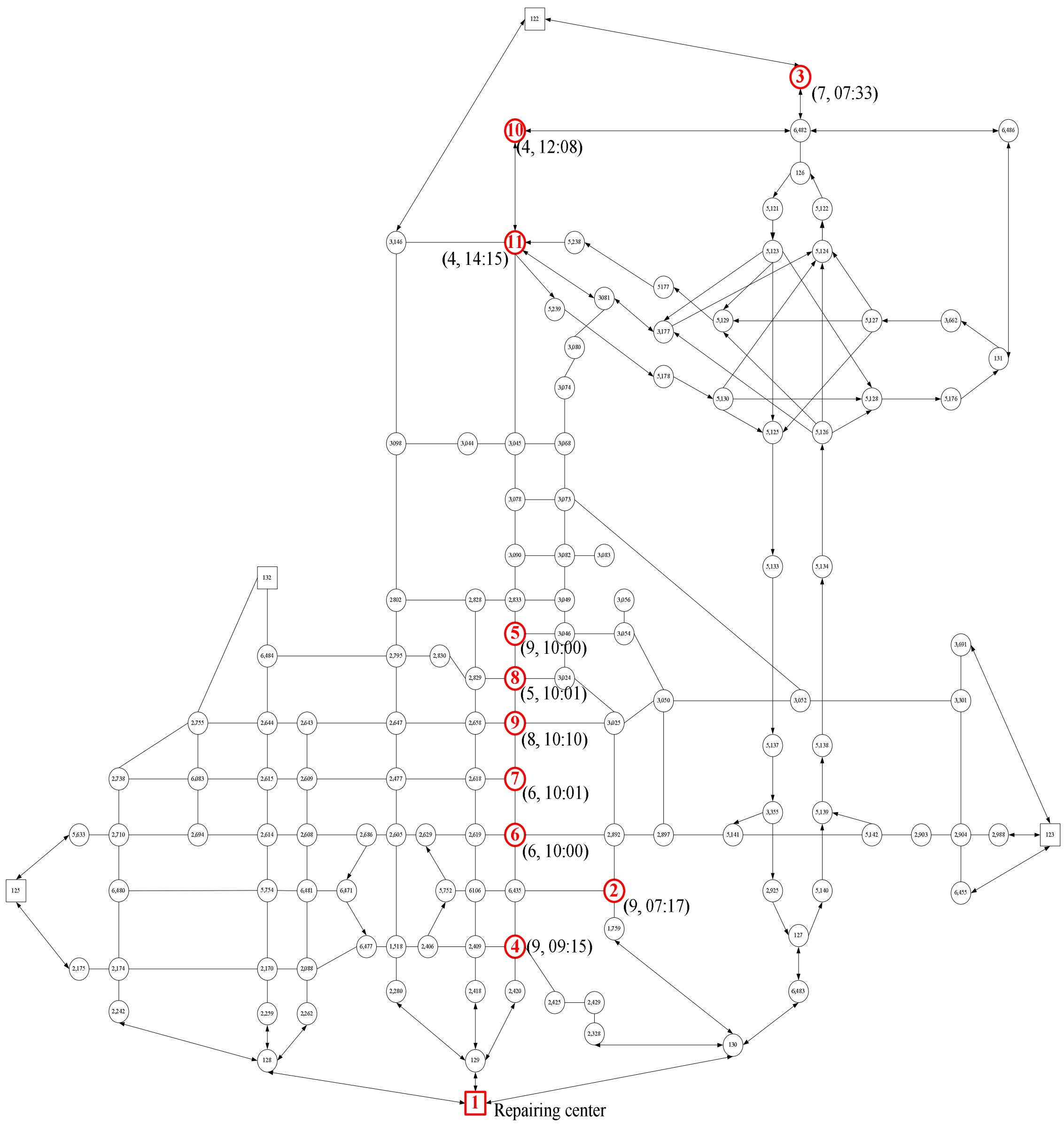
Table 2. Signal repair worksheet in the Kaohsiung City

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		8	2
II-4		6	4
II-6	1	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)

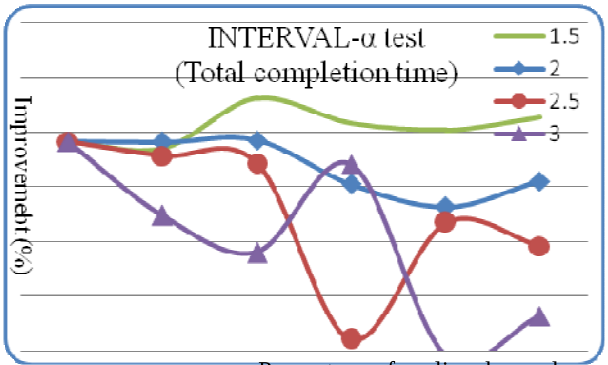
Node number	Released time	Finished time	Sequence of service	Completion time
1	--	--	--	0
2	07:00	07:59	4	59
3	07:00	**09:31**	10	151
4	07:00	07:16	1	16
5	07:00	08:44	7	104
6	07:00	07:29	2	29
7	07:00	08:15	5	75
8	07:00	08:31	6	91
9	07:00	07:43	3	43
10	07:00	09:15	9	135
11	07:00	09:00	8	120
Route	1-4-6-9-2-7-8-5-11-10-3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



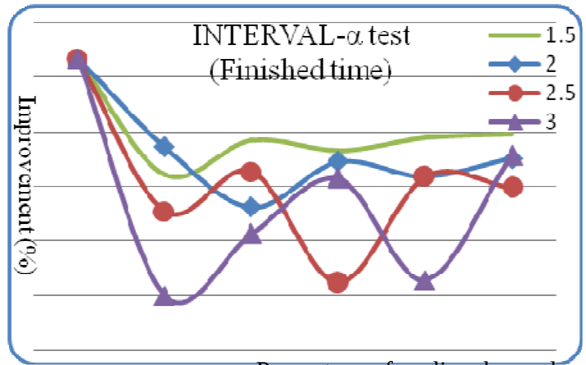


Figure 5. Sensitivity test for α in the INTERVAL strategy

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

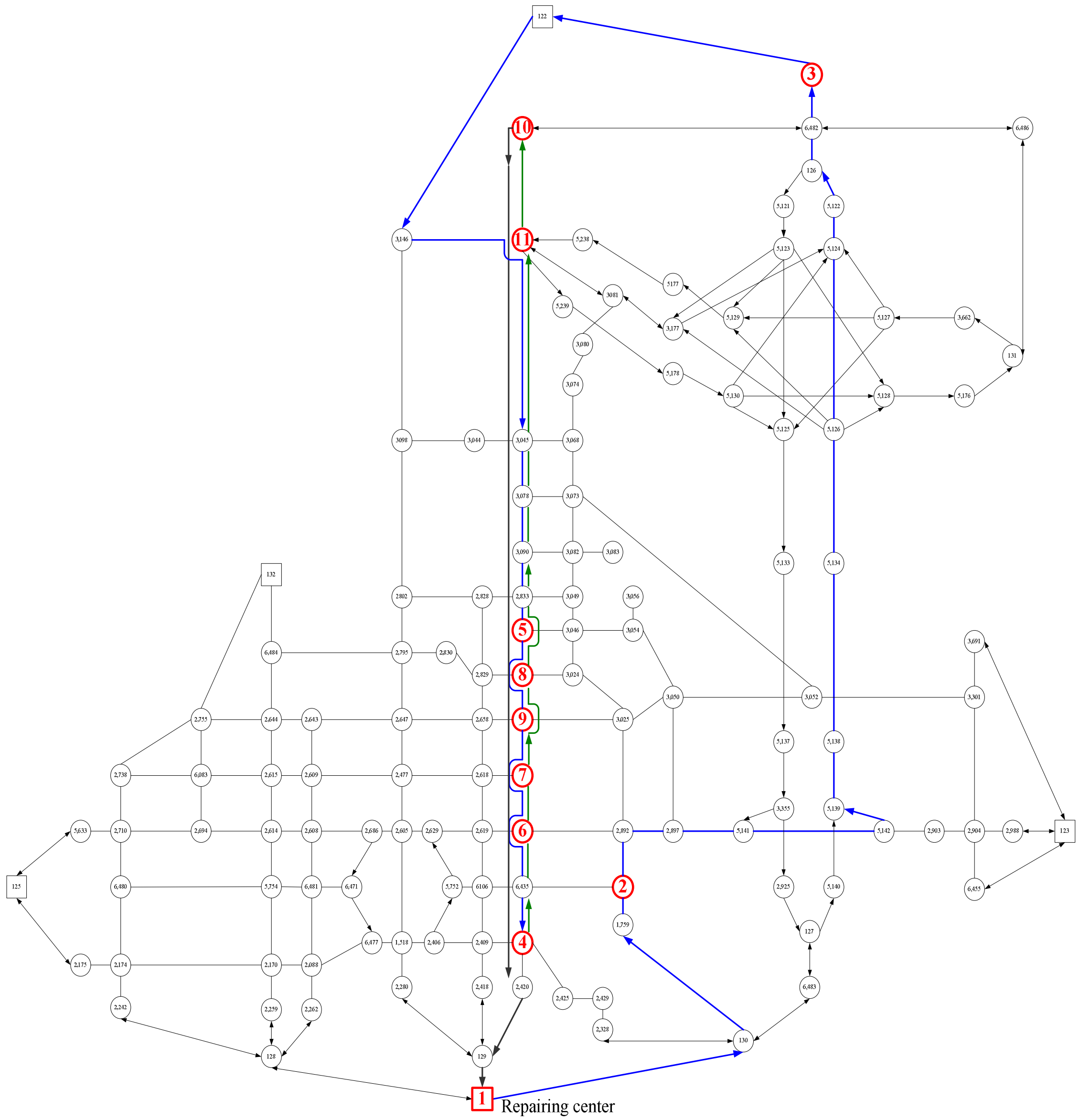
	Field data	Experiments				
		II-2	II-4	II-6	II-8	II-10
On-line demands (demand #)	2,3,4,5,6,7, 8,9,10, 11	10,11	8,9,10, 11	6,7,8,9, 10,11	4,5,6,7,8 ,9,10,11	2,3,4,5,6,7, 8,9,10, 11
Percentage of on-line demands	--	20%	40%	60%	80%	100%
Route	1-2-3-5-9-6-7-8-10-11-4	1-2-6-9-7-4-8-5-3-10-11	1-2-6-4-7-5-3-8-9-10-11	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. $Cost_{optimal}(I)$ represents the off-line optimal result for the offline version of problem P and $Cost_{online}(I)$ 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:

$$Cost_{online}(I) \leqq r\, Cost_{optimal}(I) \text{ , for all problem instances I} \qquad (16)$$

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)	$(1+\sqrt{2})^2$ (~5.828)	--
	Krumke (2000)	8	--
	Feuerstein and Stougie (2001)	9	$1+\sqrt{2}$ (~2.414)
Stochastic	Jaillet and Wagner (2006)	$4/\ln 3 - \alpha\beta/(\alpha+\beta)$	--
	Krumke *et al*. (2003)	4/ln3 (~3.6410)	7/3 (~2.333)
	Krumke (2000)	4/ln2 (~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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