Chapter 5

Computational Results

This chapter intends to show the computational results obtained during the realization of this Master Thesis.

The problem under study is composed by a several number of instances. Regardless, the basic principles of all of them are the same, their characteristics will be different from instance to instance. The different characteristics of the problem (capacity, number of available vehicles, demands on each street, service and deadheading costs associated with distinct streets and dump costs) are known for every tested instance.

This problem is composed by two distinct sets of instances. The first set, *mval* instances, contains the ones that have a fewer number of nodes (24-50) and links (43-138) which are all required. The second set, the *lpr* instances, contains a higher number of nodes (28-401) and a higher number of links (50-1056) but just a subset of these are required.

The present chapter is divided into two main sections. Each one presents the characteristics of different instances and then the results attained in each phase of the methodology explained in the previous chapter, Chapter 4. The results obtained through the application of this approach are compared with the best known value given by the work developed by [18] to evaluate the quality of the approach followed in this work.

The different tests were performed on an Intel(R) Core(TM) i5 CPU 2.40GHz with 4.00GB RAM.

5.1 *mval* Instances

This set of instances is characterized for different aspects exposed below:

- All the vehicles begin and end their trips on a special node, called depot.
- When servicing an arc/edge, this will be served just one time by the assigned vehicle.
- The deadheading cost and the service cost of each arc/edge will be different from instance to instance.

- The disposal cost isn't charged on these instances.
- The objective function of the problem is given by the sum of two different costs: deadheading cost and service cost since the disposal cost is no charged in this set of instances.
- The number of required edges is always greater than the number of required arcs.

After the description of the main characteristics of these instances, the main values of the different parameters are presented in Table 5.1.

Table 5.1: Characteristics of the *mval* instances

File	$\|N\|$	$\|A \cup E\|$	$\|A_r\|$	$\|E_r\|$
mval1A	24	55	20	35
mval1B	24	51	13	38
mval1C	24	53	17	36
mval2A	24	44	16	28
mval2B	24	52	12	40
mval2C	24	49	14	35
mval3A	24	48	15	33
mval3B	24	45	16	29
mval3C	24	43	18	25
mval4A	41	95	26	69
mval4B	41	102	19	83
mval4C	41	103	21	82
mval4D	41	104	21	83
mval5A	34	96	22	74
mval5B	34	91	35	56
mval5C	34	98	17	81
mval5D	34	92	29	63
mval6A	31	69	22	47
mval6B	31	66	22	44
mval6C	31	68	23	45
mval7A	40	86	36	50
mval7B	40	91	25	66
mval7C	40	90	28	62
mval8A	30	96	20	76
mval8B	30	91	27	64
mval8C	30	83	28	55
mval9A	50	132	32	100
mval9B	50	120	44	76
mval9C	50	125	42	83
mval9D	50	131	38	93
mval10A	50	138	32	106
mval10B	50	134	33	101
mval10C	50	136	36	100
mval10D	50	129	42	87

Column 2 of the Table 5.1 contains the number of the nodes of each instance. Column 3 shows the set of arcs and edges of the respective instance. The last two columns, 4 and 5, show the set of required arcs and required edges, respectively.

The results obtained to these instances are divided into three subsections, each one related with the corresponding phase of the methodology.

5.1.1 Phase1 - Mega-Route

Table 5.2 shows the results obtained to this set of instances tested.

Table 5.2: Phase 1 - Results obtained to *mval* Instances

Phase 1 - Mega-Route		
File	**Nodes**	**Objective Function**
mval1A	24	230
mval1B	24	261
mval1C	24	255
mval2A	24	324
mval2B	24	351
mval2C	24	313
mval3A	24	113
mval3B	24	128
mval3C	24	88
mval4A	41	566
mval4B	41	616
mval4C	41	609
mval4D	41	616
mval5A	34	597
mval5B	34	581
mval5C	34	670
mval5D	34	705
mval6A	31	326
mval6B	31	313
mval6C	31	303
mval7A	40	364
mval7B	40	412
mval7C	40	393
mval8A	30	581
mval8B	30	531
mval8C	30	527
mval9A	50	458
mval9B	50	453
mval9C	50	426
mval9D	50	478
mval10A	50	630
mval10B	50	653
mval10C	50	615
mval10D	50	562

The results presented above are divided into three columns that contain information about the number of the nodes (Column 2) and the value obtained in this phase to the objective function of the respective instance (Column 3).

These results were obtained through the use of some functions belonging to the C++ libraries from the CPLEX software. These existing functions were incorporated with the C++ code written using Visual Studio 2008 C++.

5.1.2 Phase2 - Intermediate Solution

The computational results obtained to this phase are shown in Table 5.3.

Table 5.3: Phase 2 - Results obtained to *mval* Instances

Phase 2 - Intermediate Solution			
File	**Objective Value**	**Total Demand**	**Number of Vehicles**
mval1A	272	358	2
mval1B	335	358	3
mval1C	413	328	8
mval2A	362	310	2
mval2B	427	310	3
mval2C	684	310	8
mval3A	121	137	2
mval3B	167	137	3
mval3C	196	137	7
mval4A	648	627	3
mval4B	788	627	4
mval4C	811	627	5
mval4D	1039	627	9
mval5A	689	614	3
mval5B	688	614	4
mval5C	815	614	5
mval5D	1118	614	9
mval6A	368	451	3
mval6B	368	451	4
mval6C	475	451	10
mval7A	434	559	3
mval7B	493	559	4
mval7C	603	559	9
mval8A	663	566	3
mval8B	633	566	4
mval8C	872	566	9
mval9A	556	654	3
mval9B	528	654	4
mval9C	545	654	5
mval9D	746	654	10
mval10A	705	704	3
mval10B	782	704	4
mval10C	766	704	5
mval10D	888	704	10

Table 5.3 contains information about the available vehicles (column 4), total demand collected (Column 3) and the value obtained by this phase for the objective function of the respective instance (Column 2).

5.1.3 Phase3 - Final Solution

Results obtained in this phase are exposed in Table 5.4.

Table 5.4: Phase 3 - Results obtained to *mval* Instances

Phase 3 - Final Solution				
File	**Best known value**	**Objective Value**	**Time(sec)**	**Gap(%)**
mval1A	230*	245	272	6,52%
mval1B	261*	277	233	6,13%
mval1C	309*	357	734	15,53%
mval2A	324*	350	420	8,02%
mval2B	395*	413	193	4,56%
mval2C	521*	602	700	15,55%
mval3A	115*	119	352	3,48%
mval3B	142*	151	750	6,34%
mval3C	166*	192	669	15,66%
mval4A	580*	640	660	10,34%
mval4B	650*	718	677	10,46%
mval4C	630*	762	851	20,95%
mval4D	746	949	1263	27,21%
mval5A	597*	659	809	10,39%
mval5B	613*	685	502	11,75%
mval5C	697*	786	875	12,77%
mval5D	719	928	2124	29,07%
mval6A	326*	337	355	3,37%
mval6B	317*	356	5206	12,30%
mval6C	365	457	666	25,21%
mval7A	364*	407	1079	11,81%
mval7B	412*	483	774	17,23%
mval7C	424	546	1117	28,77%
mval8A	581*	658	2147	13,25%
mval8B	531*	601	524	13,18%
mval8C	617	795	1368	28,85%
mval9A	458*	532	1020	16,16%
mval9B	453*	524	764	15,67%
mval9C	428	524	1262	22,43%
mval9D	514	696	7709	35,41%
mval10A	634*	694	935	9,46%
mval10B	661*	730	1170	10,44%
mval10C	623*	727	1405	16,69%
mval10D	643	829	2248	28,93%
Average			1230,38	15,41%
Maximum			7709	35,41%
Minimum			193	3,37%

In the above table are shown the final results for the instances under test. The second column shows the best known results obtained to the respective instance and if it's the optimal value is marked with an (*). These results were demonstrated by [18].

Column 3 contains the values achieved by the approach used in this Master Thesis. Column 4 has the time in seconds and finally, the last column contains the difference in percentage between the best known result and the value obtained by the approach followed in this work.

Results Discussion

Bellow is presented the discussion of the results attained by the new approach developed during this Master Thesis. These results were compared with the ones obtained by [18] as already mentioned.

The first phase of the methodology provides lower values for the objective function than the best known value for the same instance. This happens because the solution retrieved by this phase is an infeasible one composed by just one route travelled by one vehicle.

The solutions obtained in the second phase have values much higher than the best known values of the respective instances and that's the reason why other phase is applied. Since this solution is the one used as an input in the next phase, if it has a very high value for the objective function the Metaheuristic applied in the next phase may not be able to find a solution near to the optimal one.

The difference in percentage, called gap, between the best known result and the result achieved by this approach are depicted in the last column of the Table 5.4 and is calculated by:

$$[(BestKnownValue - ObjectiveValue) \div BestKnownValue] \times 100$$

The approach applied to obtain a solution to this set of instances doesn't provide the optimal value to none of them, as already observed in Table 5.4. As previously explained, Metaheuristics are not always able to provide the optimal solution to a given problem since it's an approximative method.

The worst scenarios were obtained for the more complex instances with a higher number of available vehicles - *mval4D, mval5D, mval6C, mval7C, mval8C, mval9D* and *mval10D* - as shown in Table 5.4. The results attained to these instances are between 15% and 36%.

The gap values verified to the instances *mval1A, mval1B, mval2A, mval2B, mval3A, mval3B* and *mval6A* are no greater than 10%. And the best value obtained is for the instance *mval6A*, with a gap near to 3.4%. In general, to the instances with a least number of vehicles are obtained good final results.

The average gap obtained to these different instances is near to the 15%, with a maximum value of 35.41% to the instance called *mval9D* that is composed by 50 nodes and 10 available vehicles.

Finally, the average CPU time obtained to this set of instances is close to 1230 s. The instance that takes longer to obtain the final solution is *mval9D* and the one that obtains faster the final solution is *mval2B*.

5.2 *lpr*-Instances

Some of the characteristics referred for the *mval* instances can be also applied to the *lpr* instances, like:

- All the vehicles begin and end their trips on a special node, called depot.

- When servicing an arc/edge it will be served just one time by that vehicle.

- The deadheading cost and the service cost of each arc/edge will be different from instance to instance

The main differences between these two types of instances lie on the characteristics listed beneath.

- The disposal cost, 300, is charged on this set of instances.

- The objective function of the *lpr* instances is given by the sum of the three different costs: deadheading cost, service cost and disposal cost.

- The instances *lpr-a* and *lpr-b* are composed for more required arcs than required edges while the instances *lpr-c* contains more required edges than required arcs.

These instances have a larger number of nodes and of required arcs/edges. This information can be observed in Table 5.5.

Table 5.5: Characteristics of the *lpr* instances

File	$\|N\|$	$\|A \cup E\|$	$\|A_r\|$	$\|E_r\|$
lpr-a-01	28	94	52	0
lpr-a-02	53	169	99	5
lpr-a-03	146	469	271	33
lpr-a-04	195	651	469	34
lpr-a-05	321	1056	748	58
lpr-b-01	28	63	45	5
lpr-b-02	53	117	92	9
lpr-b-03	163	361	279	26
lpr-b-04	248	582	493	8
lpr-b-05	401	876	764	37
lpr-c-01	28	52	11	39
lpr-c-02	53	101	23	77
lpr-c-03	163	316	61	241
lpr-c-04	277	604	142	362
lpr-c-05	369	841	416	387

Like the first Table presented in the section about the results obtained to the *mval* instances, this table contains a column to present the number of the nodes (column 2) of the respective instance, a column with information about the total required arcs plus required edges (column 3), and two separated columns comprising information about required arcs (column 4) and required edges (column 5).

The same approach used to solve the *mval* instances was followed to solve the *lpr* instances.

After the specification of the main principles, the results found to this set of instances are exposed in the next sections.

5.2.1 Phase1 - Mega-Route

The results obtained by this phase are shown in Table 5.6.

Table 5.6: Phase 1 - Results obtained to *lpr* Instances

Phase 1 - Mega-Route		
File	**Nodes**	**Objective Function**
lpr-a-01	28	13484
lpr-a-02	53	27666
lpr-a-03	146	74367
lpr-a-04	195	122732
lpr-a-05	321	193915
lpr-b-01	28	14474
lpr-b-02	53	28483
lpr-b-03	163	75792
lpr-b-04	248	122624
lpr-b-05	401	200850
lpr-c-01	28	18295
lpr-c-02	53	35152
lpr-c-03	163	106822
lpr-c-04	277	164058
lpr-c-05	369	250365

Column 2 shows the number of nodes of the respective instance and column 3 the value obtained for the objective function to the different tested instances.

It was specified a time limit to CPLEX software provide the final solution of this phase. If this maximum time is attained before the optimal solution is reached the methods used by this software should stop and return the solution found at that moment.

Observing Table 5.6 it's noticed that in some values obtained for some instances for the objective function are underlined. These values represent the instances where the maximum time (one hour) specified previously was reached.

5.2.2 Phase2 - Intermediate Solution

Table 5.7 contains the results obtained to the Phase 2 of the approach followed by this work.

Table 5.7: Phase 2 - Results obtained to *lpr* Instances

Phase 2 - Intermediate Solution			
File	**Objective Value**	**Total Demand**	**Number of Vehicles**
lpr-a-01	13591	11235	2
lpr-a-02	29457	23446	3
lpr-a-03	81430	64709	7
lpr-a-04	136283	108635	11
lpr-a-05	221676	170514	18
lpr-b-01	14950	12142	2
lpr-b-02	29575	23312	3
lpr-b-03	83000	63624	7
lpr-b-04	137664	103770	11
lpr-b-05	229634	171408	18
lpr-c-01	18927	16662	2
lpr-c-02	37581	31718	4
lpr-c-03	119294	97917	10
lpr-c-04	179548	149531	15
lpr-c-05	280251	227186	23

The aforementioned table is composed by four different columns. The first one represents the name of the respective instance, and the others contain information about the value obtained to the objective function (column 2), total demand that needs to be collected in the respective instance (column 3) and the number of available vehicles (column 4).

5.2.3 Phase3 - Final Solution

The final results obtained to this set of instances are presented in Table 5.8.

Table 5.8: Phase 3 - Results obtained to *lpr* Instances

Phase 3 - Final Solution				
File	**Best known value**	**Objective Value**	**Time(sec)**	**Gap(%)**
lpr-a-01	13484*	13554	312	0,52%
lpr-a-02	28052*	29300	1076	4,45%
lpr-a-03	76039	80665	5121	6,08%
lpr-a-04	126941	135280	8355	6,57%
lpr-a-05	202736	219715	18525	8,37%
lpr-b-01	14835*	14950	489	0,78%
lpr-b-02	28654*	29384	527	2,55%
lpr-b-03	77821	82693	5051	6,26%
lpr-b-04	126754	137277	11547	8,30%
lpr-b-05	209791	227983	53836	8,67%
lpr-c-01	18639*	18897	377	1,38%
lpr-c-02	36255*	37472	4330	3,36%
lpr-c-03	109980	118233	8196	7,50%
lpr-c-04	168441	178755	14591	6,12%
lpr-c-05	257890	278993	54467	8,18%
Average			12453,33	5,27%
Maximum			54467	8,67%
Minimum			312	0,52%

This table contains information about the best known value depicted on [18] (column 2), the value obtained by the application of the approach during the realization of this work (column 3), the CPU time in seconds (column 4) and finally the gap (column 5).

It's important to mention that if the best known value of an instance is the optimal solution it is marked with an (*).

Results Discussion

In spite of to some instances (*lpr-a-05, lpr-b-04, lpr-b-05, lpr-c-02, lpr-c-03, lpr-c-04, lpr-c-05*) the values obtained may or may not be the optimal solution to the Mega-Route of the respective instance the different values obtained by this phase of the methodology are lower than the best known results attained by [18].

In what concerns this set of instances the values obtained to the Intermediate Solution (Phase 2 of the approach developed during this work) are much higher than the best known result of the respective instance. The Metaheuristic (Phase 3) used by next phase will guarantee that the final solutions obtained are better than the solution given by the previous phase. If the value obtained to the Intermediate solution is far from the optimal solution, the Tabu Search may not find a value near to the optimal value of the respective instance.

The values obtained to the final solution of this set of instances are close to the best known value obtained by other authors. These values are between 0.52% and 8.67%.

The instance where this approach was more effective is the instance called *lpr-a-01* with a value registered to the gap close to 0.5%. The worst scenario verified was acquired for the instance *lpr-b-05* with a gap value near to 9%.

The average of the values obtained to all the instances of this set is close to 5%. This means that the solutions obtained are near to the best known results to the same instances studied by other authors, guaranteeing that this approach when applied to a set of complex instances, will be able providing good final results.

The main disadvantage verified to the more complex instances lies on the time demanded to find the final solution. To these instances the average time calculated is close to 9500 seconds. This time will increase with the complexity of the problem under study and that's the reason why in the *lpr* instances the time needed to obtain the final solutions is much higher than the one obtained to the *mval* instances.

5.3 Summary

This chapter intends to show the results obtained for two different sets of instances. The first set, called *mval* instances, comprises the simplest instances that contain (24-50) nodes and (43-138) links and all of them are required. The second set, designated *lpr* instances, is composed by complex instances with (28-401) nodes and (40-1056) links where just a subset of these are required.

To evaluate the quality of the approach followed in this work should be observed two different parameters:

1. The difference between the value obtained to the objective function by this approach and the value obtained by other authors

2. The time needed to find the final solution by the approach.

To the *mval* instances the average value obtained to the gap was near to 15% while to the *lpr* instances this value is near to 5%. Concerning the average obtained to the CPU time the *lpr* instances take much longer (12453 seconds) to obtain the final solution than the *mval* instances (1230 seconds). This happens due to the complexity of the instances that belongs to each set.

In general, the approach used in this work obtains good results to the instances under test but when it is applied to complex problems this will need much time to obtain the final solution.