Chapter 5

Experimentation and Results

For our experiments, we aim to study the following:

- Quality of the pre-processor initial solution generators.
- Comparison of BAP-GP vs other BAP-Part algorithms.
- Effectiveness of the post-processor heuristic.

This chapter first describes the design of our test data and explains the rationale behind the decisions we make in our design. Then it gives the results of our experimentations and the findings we get from our analysis of the results.

<table>
<tr><td>sect001.dat</td><td>section 1
600m</td><td>section 2
600m</td><td></td><td></td><td></td></tr>
<tr><td>sect002.dat</td><td>section 1
600m</td><td>section 2
600m</td><td>section 3
600m</td><td>section 4
600m</td><td>section 5
600m</td></tr>
<tr><td>sect003.dat</td><td>section 1
600m</td><td colspan="3">section 2
1800m</td><td>section 3
600m</td></tr>
<tr><td>sect004.dat</td><td colspan="2">section 1
1200m</td><td>section 2
600m</td><td colspan="2">section 3
1200m</td></tr>
<tr><td>sect005.dat
Brani Terminal</td><td>section 1
600m</td><td>section 2
480m</td><td>section 3
800m</td><td>section 4
200m</td><td></td></tr>
</table>

Table 5.1: Section Scenarios

5.1 Experimental Data

For our experiments, we generated 5 section scenarios, 12 vessel scenarios and 100 transshipment scenarios. We then combine these different scenarios to make up 100 data sets.

The 5 section scenarios are shown in Table 5.1, with each scenario depicting a particular port layout. We name our section data files `sect001.dat, ...,` `sect005.dat`. The first 4 section scenarios (`sect001.dat` to `sect04.dat`) are fictitious scenarios while the last one (`sect005.dat`) is the actual layout of PSA's Brani Terminal. `sect001.dat` depicts a small port while `sect002.dat` depicts a large port with equi-distant sections. `sect003.dat` and `sect004.dat` depict ports with varying section lengths. The sections are assumed to be laid out in a straight line as shown in the table. All the 5 section scenarios are hand-crafted.

The vessel and transshipment scenarios are too numerous to be listed exhaustively here. We will instead provide an overview of them and define a metric to

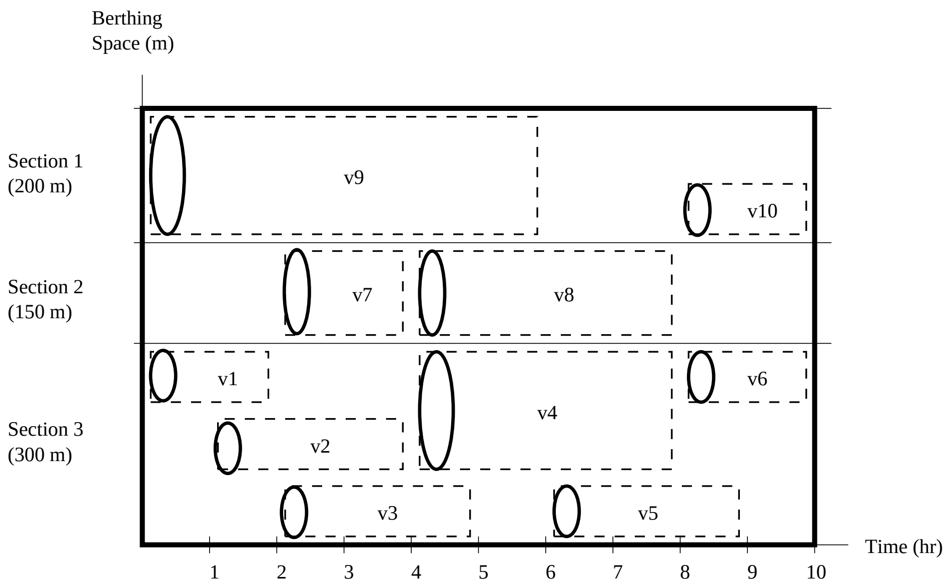

Figure 5.1: Schematic View of ABD

describe their characteristics.

The 12 vessel scenarios depict vessel schedules ranging from 60 vessels to 422 vessels, in a time window of 84 hours or $3\frac{1}{2}$ days. The vessel scenarios are then combined with section scenarios to paint a picture of a light or busy port scenario. At first glance, it may seem that the busyness of a port is proportional to the number of vessels visiting it, but it is not so trivial. For example, 60 vessels visiting a small port with 2 sections in $3\frac{1}{2}$ days would keep it very busy, while operations in a large port with 5 sections may still be light even if 200 vessels were to visit it.

To measure the busyness (or the level of activity) of a port given a vessel schedule over a certain time window, we define a metric known as the *Average*

Berth Demand (or *ABD* for short) as follows:

$$ABD = \frac{\sum_{v \in V} l_v \cdot d_v}{L \cdot T} \tag{5.1}$$

where V = set of vessels

l_v = length of vessel v

d_v = duration of stay of vessel v

= (departure-time $-$ arrival-time) of vessel v

L = total berthing length of the port

= $\sum$ all section lengths

T = time window

Figure 5.1 illustrates the schematic view of ABD. The numerator of equation (5.1) is simply the sum of the areas occupied by the outlined rectangles $v_1, \ldots, v_{10}$, while the denominator is the area occupied by the thick rectangle surrounding the ten vessels. So the ABD for Figure 5.1 is

$$\frac{100 \times 2 + 100 \times 3 + \ldots + 100 \times 2}{650 \times 10} = \frac{4400}{6500} = 0.68$$

This means that the demand over the 10 hours is 68% of the port's berthing resources. An ABD = 0 denotes an empty port or a port without any business and an ABD = 1 denotes a full port or a port at its peak busyness. The ABD could potentially be > 1.0, in which case it means the port is unable to meet its business demands. In our data generation, we did not generate any data sets with ABD >

	SC1 2 sections	**SC2** 5 sections	**SC3** 3 sections	**SC4** 3 sections	**SC5** 4 sections
ABD=0.25	d101-d105 60 vessels	-	-	-	-
ABD=0.40	d106-d110 96 vessels	d121-d125 240 vessels	d141-d145 240 vessels	d161-d165 240 vessels	d181-d185 166 vessels
ABD=0.50	d111-d115 120 vessels	d126-d130 302 vessels	d146-d150 302 vessels	d166-d170 302 vessels	d186-d190 208 vessels
ABD=0.60	d116-d120 144 vessels	d131-d135 362 vessels	d151-d155 362 vessels	d171-d175 362 vessels	d191-d195 250 vessels
ABD=0.70	-	d136-d140 422 vessels	d156-d160 422 vessels	d176-d180 422 vessels	d196-d200 292 vessels

Table 5.2: Data Set Scenarios

1.0 since it means our algorithms will by default report an infeasible solution. The 12 vessel scenarios are generated by our data generation subsystem using a section scenario and a pre-defined ABD as inputs.

Table 5.2 shows the spread of our data sets, numbered $d101$ to $d200$, across the 5 section scenarios (SC) and 5 different ABD values. Notice that each cell in the table comprises a group of 5 data sets — these 5 data sets share the same port and vessel scenarios, they differ only in the transshipment scenario. There are 20 such groups altogether. Transshipment scenarios are dependent on the port and vessel scenario combinations. It is logical to assume that a large port with many vessels would have high transshipment volumes and a small port with few vessels would have low transshipment volumes. The transshipment volume should also be positively correlated to the ABD. Thus our 100 transshipment scenarios are generated specifically for each of the above 100 data sets, using a function of the number of sections, number of vessels, ABD and some other control parameters.

$d101$ to $d110$ would be considered *small* data sets (few sections, few vessels), while $d131$ to $d140$ would be considered *big* data sets (many sections, many vessels). The data sets in the last column SC5 is used to paint scenarios for the Brani Terminal. For full details regarding the generation of our experimental data and the various scenarios, refer to [RAS99].

5.2 Quality of the Initial Solution Generators

We ran each of the 7 initial solution generators (gp001-001, ..., gp007-001)[1] over the 100 data sets and then ran BAP-GP using the initial solutions produced. We then compare the number of times BAP-GP found the best solution using each initial solution generator. The results are summarised in Table 5.3[2]. In this table, #Best gives the number of times BAP-GP found the best solution using that particular solution generator. Note that the column total = 108; it does not add up to exactly 100 because of ties in the results.

We see that methods which focus on transshipment (gp003-001, gp004-001 and gp006-001) produce better solutions. This makes sense since the transshipment cost is a major component in our objective function. In particular, gp003-001 and

[1]Each solution generator is suffixed with 001 as part of our software development convention.

[2]gp001-001 is ran over the same random seed for each of the 100 data sets.

Algo Code	Algorithm Characteristics	#Best
gp001-001	Random	13
gp002-001	By vessel length	8
gp003-001	By vessel transshipment volume	28
gp004-001	Simple clustering	18
gp005-001	By TZ density, vessel length	10
gp006-001	By TZ density, vessel transshipment volume	23
gp007-001	By TZ density, #TZ spanned by vessel	8

Table 5.3: Summary of Initial Solution Generator Results

gp006-001 assign vessels with highest transshipment volumes first, and doing so probably cause these vessels to be used as seeds to attract other vessels into the section.

Tables A.1 and A.2 give the detailed comparison of the objective values obtained by each of the algorithms over the 100 data sets. Tables A.3 and A.4 give the summary of the best result obtained for each data set. #Se indicates the number of sections and #Ve indicates the number of vessels in the data set. Together they give an idea of the "size" of the data set. #U is the number of unallocated vessels in the final solution and #P is the number of passes before BAP-GP settles into a local optimal. The actual running time and the average distance moved per container (AvgD)[3] are also given.

We point out the following observations from Tables A.3 and A.4:

1. The number of passes is generally small and BAP-GP will converge quickly into a local optimal.

[3]We defined this metric recently as it may be useful in future as a quality indicator.

2. The running times for the data sets are all below 10 sec. These experiments were run on a Pentium-II 333 MHz machine with 128 MB RAM. The fast running times provide evidence that our algorithm is efficiently implemented. As mentioned in Section 5.1, $d131$ to $d140$ are the big data sets and from Table A.3, we see that they have the longest running time. The total time taken for all 700 runs (100 data sets $\times$ 7 generators) is $\approx$ 20 mins.

3. $d139$ and $d192$ each has 1 unallocated vessel but the penalty value is 0. The reason for this is that our data generation system generated a vessel with 0 transshipment volume (ie. no import and export, and no transshipment with other vessels) for these 2 data sets. Such an anomalous vessel is irrelevant to our problem and we safely can ignore it[4].

4. The penalty values for $d191, d193, d195, d196, d197, d199$ and $d200$ are non-zero, meaning that BAP-GP is unable to find a feasible solution. We call these *hard* data sets.

[4]This anomaly is due to a minor bug in the transshipment generation algorithm. Of the 100 data sets, only $d139$ and $d192$ have such anomaly and only 1 affected vessel each.

5.3 Comparison of BAP-GP with other BAP-Part Algorithms

To evaluate the strength of our BAP-GP algorithm, we would like to compare our results with established benchmarks. Unfortunately, there are no existing benchmarks for the BAP. We also had difficulty obtaining real world data because such data are classified information in the commercial world. But we do have results from the different BAP research works done in the RAS Group. They are:

1. Genetic algorithm from [LoLe96], termed *BAP-GA-I*[5].
2. Genetic algorithm from [FoLe00], termed *BAP-GA*.
3. Branch-and-bound exhaustive search from [XuLe99], termed *BAP-BB*.

We will then compare the results of BAP-GP with those obtained from the above algorithms.

For BAP-GA-I and BAP-GA, we select the best results obtained by them on the 100 data sets and do a direct comparison with BAP-GP. Unfortunately, we are unable to run BAP-BB through the 100 data sets as there are too many combinations to consider — n vessels and m sections give rise to m^n possible combinations, since each of the n vessels can be assigned to any of the m sections. Thus even the smallest data set of 60 vessels and 2 sections has 2^{60} possible solutions, an

[5] In the RAS Group, this research is commonly called BAP GA Phase I

intractable magnitude for the branch-and-bound exhaustive search algorithm. As a result, we will instead run our BAP-GP through the test data obtained from [XuLe99], which are specially generated data sets (with $n < 45$ and $m < 5$) that the BAP-BB can solve within a reasonable amount of time, and compare this set of results instead.

5.3.1 Comparing BAP-GP with BAP-GA-I and BAP-GA

We took the best results from the first experiment mentioned in Section 5.2 of 700 runs (7 runs per data set) and compare them with those obtained from BAP-GA-I and BAP-GA. The results for BAP-GA-I were obtained from an old experiment run using [LoLe96] in late 1997/early 1998. The entire experiment took about 1 month to complete[6]. For BAP-GA, each data set went through 5 runs of the GA heuristic with different random seeds and the best result among the 5 runs was selected for each data set. BAP-GA took about 2 days to complete all the 500 runs on a K6-2 350 MHz machine with 128 MB RAM. The results are shown in Tables 5.4 and 5.5. The *Best* column shows the best or minimum objective value from the three algorithms and the *Ratio* column tells how far off BAP-GP is from the best solution. The ratio is computed as

$$Ratio = \frac{BAPGP - Best}{Best} \times 100\% \tag{5.2}$$

[6]Unfortunately we do not have the actual timings or system configuration for comparison.

A ratio of 0 means that BAP-GP found the best solution. The higher the ratio, the further BAP-GP is from the best.

From the tables, we make the following observations:

- For data sets $d191$ and $d195$, at least one of the GA algorithms found the best solution while BAP-GP is unable to find a feasible solution. Hence the ratio value is very high.

- For data sets $d193, d196, d197, d199$ and $d200$, all 3 algorithms are unable to find any feasible solution, and because each algorithm imposes a different penalty function, it makes no sense to compare the objective values obtained. Therefore we do not compute the ratio.

- The performance of BAP-GP can be summarised as follows:

Ratio (R)	*# of Data Sets*	Cumulative
$R = 0$ (Found best)	20	20
$0 < R \leq 5\%$	16	36
$5 < R \leq 10\%$	17	53
$10 < R \leq 15\%$	18	71
$15 < R \leq 20\%$	5	76
$R > 20\%$	24	100

(the figure 24 in last row includes above 5 infeasible solutions)

Data	#Se	#Ve	BAP-GP	BAP-GA-I	BAP-GA	Best	Ratio (%)
d101	2	60	216,000	216,000	216,000	216,000	0
d102	2	60	141,600	141,600	141,600	141,600	0
d103	2	60	180,000	180,000	180,000	180,000	0
d104	2	60	166,800	148,800	148,800	148,800	12
d105	2	60	144,600	144,600	144,600	144,600	0
d106	2	96	446,700	396,900	383,700	383,700	16
d107	2	96	415,800	389,400	451,200	389,400	7
d108	2	96	422,400	430,200	464,400	422,400	0
d109	2	96	310,800	322,200	310,800	310,800	0
d110	2	96	489,600	483,600	458,400	458,400	7
d111	2	120	586,800	567,000	566,400	566,400	4
d112	2	120	537,900	563,100	545,100	537,900	0
d113	2	120	570,300	537,900	561,900	537,900	6
d114	2	120	634,200	595,800	574,200	574,200	10
d115	2	120	601,800	610,200	547,200	547,200	10
d116	2	144	788,100	800,100	800,100	788,100	0
d117	2	144	841,200	799,200	813,000	799,200	5
d118	2	144	975,900	942,300	850,500	850,500	15
d119	2	144	966,900	917,700	944,100	917,700	5
d120	2	144	907,200	895,200	824,400	824,400	10
d121	5	240	2,555,100	2,586,300	2,267,100	2,267,100	13
d122	5	240	2,467,200	2,638,800	2,549,400	2,467,200	0
d123	5	240	2,539,800	2,791,800	2,513,400	2,513,400	1
d124	5	240	2,752,200	2,668,800	2,501,400	2,501,400	10
d125	5	240	2,525,700	2,790,900	2,642,700	2,525,700	0
d126	5	302	4,077,000	4,214,400	3,802,800	3,802,800	7
d127	5	302	4,417,200	4,284,600	3,882,000	3,882,000	14
d128	5	302	4,336,200	4,392,600	3,918,600	3,918,600	11
d129	5	302	4,308,600	4,330,200	4,029,000	4,029,000	7
d130	5	302	4,030,200	4,083,000	3,955,200	3,955,200	2
d131	5	362	5,461,800	5,583,600	5,366,400	5,366,400	2
d132	5	362	5,861,400	5,882,400	5,398,200	5,398,200	9
d133	5	362	5,607,300	5,964,900	5,475,300	5,475,300	2
d134	5	362	5,940,000	6,107,400	5,502,600	5,502,600	8
d135	5	362	6,143,700	6,285,900	5,753,700	5,753,700	7
d136	5	422	8,339,700	9,226,300	8,297,100	8,297,100	1
d137	5	422	9,242,100	9,425,700	8,678,100	8,678,100	6
d138	5	422	9,009,600	9,330,800	8,476,800	8,476,800	6
d139	5	422	7,607,700	8,399,100	7,369,500	7,369,500	3
d140	5	422	8,702,400	9,649,600	8,813,400	8,702,400	0
d141	3	240	206,700	186,300	186,300	186,300	11
d142	3	240	133,200	133,200	133,200	133,200	0
d143	3	240	318,600	243,000	243,000	243,000	31
d144	3	240	162,000	162,000	162,000	162,000	0
d145	3	240	347,100	332,700	339,900	332,700	4
d146	3	302	1,425,600	1,160,400	1,161,600	1,160,400	23
d147	3	302	1,288,200	1,108,200	988,200	988,200	30
d148	3	302	1,389,600	1,146,000	984,000	984,000	41
d149	3	302	1,567,800	1,249,800	1,074,600	1,074,600	46
d150	3	302	1,486,800	1,112,400	943,200	943,200	58

Table 5.4: 1st Comparison of BAP-GP, BAP-GA-I and BAP-GA (a)

Data	#Se	#Ve	BAP-GP	BAP-GA-I	BAP-GA	Best	Ratio (%)
d151	3	362	2,356,200	2,427,000	2,200,200	2,200,200	7
d152	3	362	2,845,800	2,670,600	2,085,000	2,085,000	36
d153	3	362	2,550,300	2,784,300	2,225,100	2,225,100	15
d154	3	362	2,801,400	2,685,000	2,100,600	2,100,600	33
d155	3	362	3,175,500	3,015,900	2,310,300	2,310,300	37
d156	3	422	4,823,100	5,108,700	3,836,700	3,836,700	26
d157	3	422	5,312,700	5,305,500	4,232,700	4,232,700	26
d158	3	422	5,137,800	5,559,000	4,110,600	4,110,600	25
d159	3	422	4,440,900	4,578,900	3,436,500	3,436,500	29
d160	3	422	5,518,800	5,954,400	4,195,200	4,195,200	32
d161	3	240	1,752,900	1,617,000	1,404,600	1,404,600	25
d162	3	240	1,614,600	1,884,600	1,411,200	1,411,200	14
d163	3	240	1,812,600	1,869,300	1,536,300	1,536,300	18
d164	3	240	1,647,900	1,810,800	1,494,000	1,494,000	10
d165	3	240	2,266,800	2,274,900	1,766,400	1,766,400	28
d166	3	302	3,325,200	3,597,000	3,168,600	3,168,600	5
d167	3	302	3,692,400	3,692,400	3,326,100	3,326,100	11
d168	3	302	3,717,600	3,685,200	3,283,800	3,283,800	13
d169	3	302	4,094,700	3,964,200	3,295,500	3,295,500	24
d170	3	302	3,700,800	3,780,000	3,098,700	3,098,700	19
d171	3	362	5,207,100	5,077,500	4,576,200	4,576,200	14
d172	3	362	5,329,500	5,249,400	4,745,400	4,745,400	12
d173	3	362	4,908,300	5,121,600	4,992,900	4,908,300	0
d174	3	362	5,005,500	5,273,700	4,827,300	4,827,300	4
d175	3	362	5,341,200	5,348,400	5,143,200	5,143,200	4
d176	3	422	6,947,700	7,157,400	6,368,100	6,368,100	9
d177	3	422	6,815,700	7,203,600	6,511,500	6,511,500	5
d178	3	422	7,494,600	7,334,400	6,627,900	6,627,900	13
d179	3	422	6,484,200	6,816,300	6,420,300	6,420,300	1
d180	3	422	7,230,000	7,463,100	6,600,000	6,600,000	10
d181	4	166	1,487,890	1,500,580	1,720,570	1,487,890	0
d182	4	166	1,718,510	1,712,810	1,881,990	1,712,810	0
d183	4	166	1,477,830	1,516,910	1,761,410	1,477,830	0
d184	4	166	1,439,050	1,531,580	1,651,460	1,439,050	0
d185	4	166	1,731,140	1,632,750	1,834,140	1,632,750	6
d186	4	208	2,248,270	2,318,590	2,442,420	2,248,270	0
d187	4	208	2,236,660	2,187,210	2,243,480	2,187,210	2
d188	4	208	2,224,100	2,150,290	2,341,390	2,150,290	3
d189	4	208	1,993,370	2,054,300	2,074,320	1,993,370	0
d190	4	208	2,986,860	2,688,430	2,520,180	2,520,180	19
d191	4	250	63,819,140	4,063,110	307,605,000	4,063,110	1,471
d192	4	250	3,270,610	3,474,960	3,282,910	3,270,610	0
d193	4	250	63,789,310	205,567,000	310,127,000	-	-
d194	4	250	3,412,110	3,517,310	2,996,230	2,996,230	14
d195	4	250	153,613,980	3,445,220	511,922,000	3,445,220	4,359
d196	4	292	139,872,620	1,070,010,000	1,240,130,000	-	-
d197	4	292	245,210,330	942,279,000	1,241,290,000	-	-
d198	4	292	4,587,960	4,837,970	3,915,540	3,915,540	17
d199	4	292	64,880,180	412,741,000	105,690,000	-	-
d200	4	292	95,147,290	208,987,000	813,084,000	-	-

Table 5.5: 1st Comparison of BAP-GP, BAP-GA-I and BAP-GA (b)

This performance is reasonable when we consider the running times of the 3 algorithms. BAP-GP solves each data set in a matter of seconds, even when running through all the 7 initial solution generators. Comparatively, both BAP-GA-I and BAP-GA take a long time to solve each data set. This is due to the GA algorithms searching through a very large solution space.

From the above observation, we decided to boost the performance of BAP-GP by performing many standard random restarts and selecting the best result obtained. To do so, we capitalised on the very fast running time of BAP-GP and conducted a second experiment. Here, we ran each data set through 100 different starting configurations by using the gp001 (random) initial solution generator with 100 different random seeds. The entire experiment consisted of 10,000 runs (100 data sets $\times$ 100 runs each). Tables A.5 and A.6 summarise the best results from this second experiment. The 100 runs per data set are identified by the codes gp001-001 to gp001-200 where the suffixes 101, ..., 200 represent the 100 random seeds used. Comparing Tables A.3, A.4, A.5 and A.6, we make the following observations:

1. The solutions of second experiment are better than the first in 79 out of the 100 data sets and there are 8 ties. This improvement is expected as running BAP-GP through more different starting solutions should produce better solutions.

2. For the data sets $d191, d193, d195, d196, d197, d199, d200$, the second experi-

ment is still unable to locate a feasible solution. However, it found improved solutions to $d195, d197, d200$ with lower penalty values.

3. Of particular interest also are the smaller numbers of unassigned vessels in $d195, d196, d197$. These numbers could be of practical use in a real world situation as they imply that fewer vessels would have to be delayed, thus enabling the port to reduce its losses.

4. For the data sets $d139$ and $d192$ with 0 transshipment vessels, we obtained a new solution to $d139$ with even the anomalous vessel being assigned and the transshipment cost is actually improved. For $d192$, the anomalous vessel is assigned at the expense of increased transshipment cost.

Then we combined the results from the first and second experiments, for a grand total of 107 runs per data set or 10,700 runs for all 100 data sets, and pick the best solutions for a second round of comparison with BAP-GA-I and BAP-GA. Tables A.7 and A.8 summarise the best BAP-GP results obtained from all the 10,700 runs by combining the best results found in Tables A.3, A.4, A.5 and A.6.

Tables A.9 and A.10 show the times taken by BAP-GP and BAP-GA. BAP-GP performed 107 runs on each data set while BAP-GA did 5 runs. BAP-GP took 18,188 sec or $\approx$ 5 hours for all 10,700 runs. BAP-GA took 148,132 sec or $\approx$ 41 hours for all 500 runs. BAP-GA is about 100 times slower than BAP-GP on a single run. From these timings, we see that BAP-GA has a time advantage of a factor of about 8 over BAP-GP. The results for the second round of comparison are shown in Tables 5.6 and 5.7.

The new performance of BAP-GP can be summarised as follows:

Ratio (R)	*# of Data Sets*	Cumulative
$R = 0$ (Found best)	45	45
$0 < R \leq 5\%$	22	67
$5 < R \leq 10\%$	7	74
$10 < R \leq 15\%$	7	81
$15 < R \leq 20\%$	4	85
$R > 20\%$	15	100

- The number of best solutions found more than doubled, while those within 5% of the best increased by about a third. As can be seen, there is indeed a major improvement to the overall BAP-GP results when we invest more time into running the program.

Figure 5.2 shows the pictorial view of our results. The dark shaded areas show the data sets in which BAP-GP has difficulty in obtaining a good solution. In particular, we see SC5 (Brani Terminal) giving BAP-GP problems due to the short 200m section in it. This causes the infeasible solutions when the ABD is increased. As for SC3, while BAP-GP has no problems finding feasible solutions, the GA algorithms produce more optimal solutions when the ABD is increased.

Data	#Se	#Ve	BAP-GP	BAP-GA-I	BAP-GA	Best	Ratio (%)
d101	2	60	216,000	216,000	216,000	216,000	0
d102	2	60	141,600	141,600	141,600	141,600	0
d103	2	60	180,000	180,000	180,000	180,000	0
d104	2	60	148,800	148,800	148,800	148,800	0
d105	2	60	144,600	144,600	144,600	144,600	0
d106	2	96	382,500	396,900	383,700	382,500	0
d107	2	96	379,800	389,400	451,200	379,800	0
d108	2	96	422,400	430,200	464,400	422,400	0
d109	2	96	310,800	322,200	310,800	310,800	0
d110	2	96	474,000	483,600	458,400	458,400	3
d111	2	120	568,200	567,000	566,400	566,400	0
d112	2	120	488,700	563,100	545,100	488,700	0
d113	2	120	530,700	537,900	561,900	530,700	0
d114	2	120	567,000	595,800	574,200	567,000	0
d115	2	120	546,600	610,200	547,200	546,600	0
d116	2	144	766,500	800,100	800,100	766,500	0
d117	2	144	773,400	799,200	813,000	773,400	0
d118	2	144	963,300	942,300	850,500	850,500	13
d119	2	144	921,900	917,700	944,100	917,700	0
d120	2	144	859,200	895,200	824,400	824,400	4
d121	5	240	2,400,300	2,586,300	2,267,100	2,267,100	6
d122	5	240	2,437,200	2,638,800	2,549,400	2,437,200	0
d123	5	240	2,539,800	2,791,800	2,513,400	2,513,400	1
d124	5	240	2,464,800	2,668,800	2,501,400	2,464,800	0
d125	5	240	2,525,700	2,790,900	2,642,700	2,525,700	0
d126	5	302	3,948,600	4,214,400	3,802,800	3,802,800	4
d127	5	302	3,940,200	4,284,600	3,882,000	3,882,000	1
d128	5	302	4,110,600	4,392,600	3,918,600	3,918,600	5
d129	5	302	4,044,000	4,330,200	4,029,000	4,029,000	0
d130	5	302	3,879,600	4,083,000	3,955,200	3,879,600	0
d131	5	362	5,461,800	5,583,600	5,366,400	5,366,400	2
d132	5	362	5,513,400	5,882,400	5,398,200	5,398,200	2
d133	5	362	5,511,900	5,964,900	5,475,300	5,475,300	1
d134	5	362	5,658,600	6,107,400	5,502,600	5,502,600	3
d135	5	362	5,679,900	6,285,900	5,753,700	5,679,900	0
d136	5	422	8,016,900	9,226,300	8,297,100	8,016,900	0
d137	5	422	7,830,900	9,425,700	8,678,100	7,830,900	0
d138	5	422	8,035,200	9,330,800	8,476,800	8,035,200	0
d139	5	422	7,476,300	8,399,100	7,369,500	7,369,500	1
d140	5	422	8,127,000	9,649,600	8,813,400	8,127,000	0
d141	3	240	186,300	186,300	186,300	186,300	0
d142	3	240	133,200	133,200	133,200	133,200	0
d143	3	240	256,200	243,000	243,000	243,000	5
d144	3	240	162,000	162,000	162,000	162,000	0
d145	3	240	347,100	332,700	339,900	332,700	4
d146	3	302	1,137,600	1,160,400	1,161,600	1,137,600	0
d147	3	302	1,195,800	1,108,200	988,200	988,200	21
d148	3	302	1,209,600	1,146,000	984,000	984,000	23
d149	3	302	1,378,200	1,249,800	1,074,600	1,074,600	28
d150	3	302	1,264,800	1,112,400	943,200	943,200	34

Table 5.6: 2nd Comparison of BAP-GP, BAP-GA-I and BAP-GA (a)

Data	#Se	#Ve	BAP-GP	BAP-GA-I	BAP-GA	Best	Ratio (%)
d151	3	362	2,356,200	2,427,000	2,200,200	2,200,200	7
d152	3	362	2,409,000	2,670,600	2,085,000	2,085,000	16
d153	3	362	2,516,700	2,784,300	2,225,100	2,225,100	13
d154	3	362	2,317,800	2,685,000	2,100,600	2,100,600	10
d155	3	362	2,778,300	3,015,900	2,310,300	2,310,300	20
d156	3	422	4,453,500	5,108,700	3,836,700	3,836,700	16
d157	3	422	4,683,900	5,305,500	4,232,700	4,232,700	11
d158	3	422	4,973,400	5,559,000	4,110,600	4,110,600	21
d159	3	422	4,169,700	4,578,900	3,436,500	3,436,500	21
d160	3	422	5,112,000	5,954,400	4,195,200	4,195,200	22
d161	3	240	1,481,100	1,617,000	1,404,600	1,404,600	5
d162	3	240	1,605,600	1,884,600	1,411,200	1,411,200	14
d163	3	240	1,800,000	1,869,300	1,536,300	1,536,300	17
d164	3	240	1,647,900	1,810,800	1,494,000	1,494,000	10
d165	3	240	2,088,600	2,274,900	1,766,400	1,766,400	18
d166	3	302	3,325,200	3,597,000	3,168,600	3,168,600	5
d167	3	302	3,384,600	3,692,400	3,326,100	3,326,100	2
d168	3	302	3,248,700	3,685,200	3,283,800	3,248,700	0
d169	3	302	3,549,300	3,964,200	3,295,500	3,295,500	8
d170	3	302	3,429,900	3,780,000	3,098,700	3,098,700	11
d171	3	362	4,596,900	5,077,500	4,576,200	4,576,200	0
d172	3	362	4,869,600	5,249,400	4,745,400	4,745,400	3
d173	3	362	4,833,600	5,121,600	4,992,900	4,833,600	0
d174	3	362	4,804,800	5,273,700	4,827,300	4,804,800	0
d175	3	362	5,120,700	5,348,400	5,143,200	5,120,700	0
d176	3	422	6,393,300	7,157,400	6,368,100	6,368,100	0
d177	3	422	6,815,700	7,203,600	6,511,500	6,511,500	5
d178	3	422	6,477,600	7,334,400	6,627,900	6,477,600	0
d179	3	422	6,179,100	6,816,300	6,420,300	6,179,100	0
d180	3	422	6,527,100	7,463,100	6,600,000	6,527,100	0
d181	4	166	1,473,190	1,500,580	1,720,570	1,473,190	0
d182	4	166	1,648,960	1,712,810	1,881,990	1,648,960	0
d183	4	166	1,477,830	1,516,910	1,761,410	1,477,830	0
d184	4	166	1,383,670	1,531,580	1,651,460	1,383,670	0
d185	4	166	1,613,860	1,632,750	1,834,140	1,613,860	0
d186	4	208	2,156,140	2,318,590	2,442,420	2,156,140	0
d187	4	208	2,096,270	2,187,210	2,243,480	2,096,270	0
d188	4	208	2,029,300	2,150,290	2,341,390	2,029,300	0
d189	4	208	1,915,000	2,054,300	2,074,320	1,915,000	0
d190	4	208	2,528,220	2,688,430	2,520,180	2,520,180	0
d191	4	250	63,819,140	4,063,110	307,605,000	4,063,110	1,471
d192	4	250	3,270,610	3,474,960	3,282,910	3,270,610	0
d193	4	250	63,318,180	205,567,000	310,127,000	-	-
d194	4	250	3,176,550	3,517,310	2,996,230	2,996,230	6
d195	4	250	107,956,080	3,445,220	511,922,000	3,445,220	3,034
d196	4	292	139,872,620	1,070,010,000	1,240,130,000	-	-
d197	4	292	229,344,330	942,279,000	1,241,290,000	-	-
d198	4	292	4,269,070	4,837,970	3,915,540	3,915,540	9
d199	4	292	64,880,180	412,741,000	105,690,000	-	-
d200	4	292	64,169,870	208,987,000	813,084,000	-	-

Table 5.7: 2nd Comparison of BAP-GP, BAP-GA-I and BAP-GA (b)

	SC1 2 sections	**SC2** 5 sections	**SC3** 3 sections	**SC4** 3 sections	**SC5** 4 sections
ABD=0.25	d101-d105 60 vessels				
ABD=0.40	d106-d110 96 vessels	d121-d125 240 vessels	d141-d145 240 vessels	d161-d165 240 vessels	d181-d185 166 vessels
ABD=0.50	d111-d115 120 vessels	d126-d130 302 vessels	d146-d150 302 vessels	d166-d170 302 vessels	d186-d190 208 vessels
ABD=0.60	d116-d120 144 vessels	d131-d135 362 vessels	d151-d155 362 vessels	d171-d175 362 vessels	d191-d195 250 vessels
ABD=0.70		d136-d140 422 vessels	d156-d160 422 vessels	d176-d180 422 vessels	d196-d200 292 vessels

Problematic Data Sets

Figure 5.2: Pictorial View of Results

This could be due to the GA algorithms having the freedom to search through a larger solution space for the large 1800m middle section affords many combinations to assign vessels. The light shaded areas in SC4 show the data sets in which BAP-GP produces mediocre solutions. We do not see any particular reason for this; this deficiency would most likely go away if we allow BAP-GP to run through more different starting configurations. After all, BAP-GA took 8 times longer than BAP-GP to find these solutions.

Data	#Se	#Ve	BAP-GP	BAP-BB	Best	Ratio (%)
d212	2	27	160,800	160,800	160,800	0
d213	2	27	162,300	162,300	162,300	0
d215	2	27	147,900	144,900	144,900	2
d217	2	33	183,000	169,200	169,200	8
d341	3	29	48,600	48,600	48,600	0
d342	3	29	64,500	64,500	64,500	0
d343	3	29	56,700	56,700	56,700	0
d344	3	29	63,900	63,900	63,900	0
d345	3	29	96,900	96,900	96,900	0
d346	3	35	197,400	197,400	197,400	0
d347	3	35	110,400	110,400	110,400	0
d348	3	35	201,300	201,300	201,300	0
d349	3	35	93,900	93,900	93,900	0
d350	3	35	124,500	124,500	124,500	0
d351	3	43	322,200	322,200	322,200	0
d352	3	43	273,300	273,300	273,300	0

Table 5.8: Comparison of BAP-GP and BAP-BB

5.3.2 Comparing BAP-GP with BAP-BB

The branch-and-bound BAP-BB is able to find the optimum solutions for small data sets, with number of vessels $n < 45$, thus providing us with an absolute lower bound for evaluation. We run BAP-GP through 16 data sets obtained from the BAP-BB research ([XuLe99]). Each data set is run through gp001-001, ..., gp007-001 and through gp001-101, ..., gp001-200. The best results obtained are summarised in Table A.11. The total time taken to complete the entire experiment with 16 data sets and 107 runs on each data set (for a total of 1,712 runs) is ≈ 2 mins, as each data set is very small.

Table 5.8 compares our results with the optimum results from BAP-BB. Observe that

	Before post-processor			After post-processor		
Data	**#U**	**Penalty**	**Algo**	**#U**	**Penalty**	**Algo**
d191	1	60000000	gp005-001	No improvement		
d193	1	60000000	gp001-195	No improvement		
d195	1	104000000	gp001-129	1	90000000	gp001-143
d196	3	135000000	gp006-001	2	105000000	gp006-001
d197	3	224000000	gp001-111	No improvement		
d199	1	60000000	gp003-001	No improvement		
d200	1	60000000	gp001-199	No improvement		

Table 5.9: Summary of Post-Processor Heuristic Results

- BAP-GP found the optimum solution for 14 out of 16 data sets or 87.5% of the data sets used in this experiment.
- For the remaining 2 data sets $d215$ and $d217$, the solutions found by BAP-GP are respectively 2% and 8% off the optimum.

These results, together with those from Section 5.3.1, suggest that BAP-GP is very effective for small data sets (2 or 3 sections, $\approx$ 200 vessels or less).

5.4 Post-Processor Heuristic Result

We ran the post-processor heuristic on the data sets with infeasible solution, namely $d191, d193, d195, d196, d197, d199, d200$. For each data set, we first ran it through gp001-101, ..., gp001-200 to obtain 100 different infeasible solutions, and we then ran these 100 infeasible solutions through the post-processor heuristic. Our aim is to (i) obtain a feasible solution, or failing which, (ii) obtain a better infeasible solution with a lower penalty. Table 5.9 summarises our results.

We observe the following:

- The heuristic is unable to find a feasible solution for all the data sets. It did find better infeasible solutions for $d195$ and $d196$, though for all other data sets, no better solution can be found.

- For $d195$, an improvement in penalty is found. As the penalty is related to the number of containers the vessel has to transship, the unassigned vessel in the post-processor solution has a lower transshipment volume than the vessel in the initial solution, thus accounting for the lower penalty.

- For $d196$, the number of unassigned vessels drops from 3 to 2 and subsequently the penalty is also lower. This is the best improvement found so far.

The performance of the post-processor heuristic is not good because the heuristic is a simple one. Referring back to Figure 3.11, we want to know if it is at all feasible to assign all the 18 vessels in the problematic time zone 69. What we did was to construct a data set consisting of these 18 vessels and ran BAP-BB on it. After a few hours, BAP-BB returned the solution as shown in Figure 5.3. Here, we see that it is indeed feasible to assign all the 18 vessels. To do so, however, requires us to swap groups of vessels. For instance, we have to move v_7, v_{41}, v_{131} from s_2 to s_3 and move v_{91}, v_{140} from s_3 to s_2. However, the heuristic is unable to find such a solution because it only considers pairs of vessels.

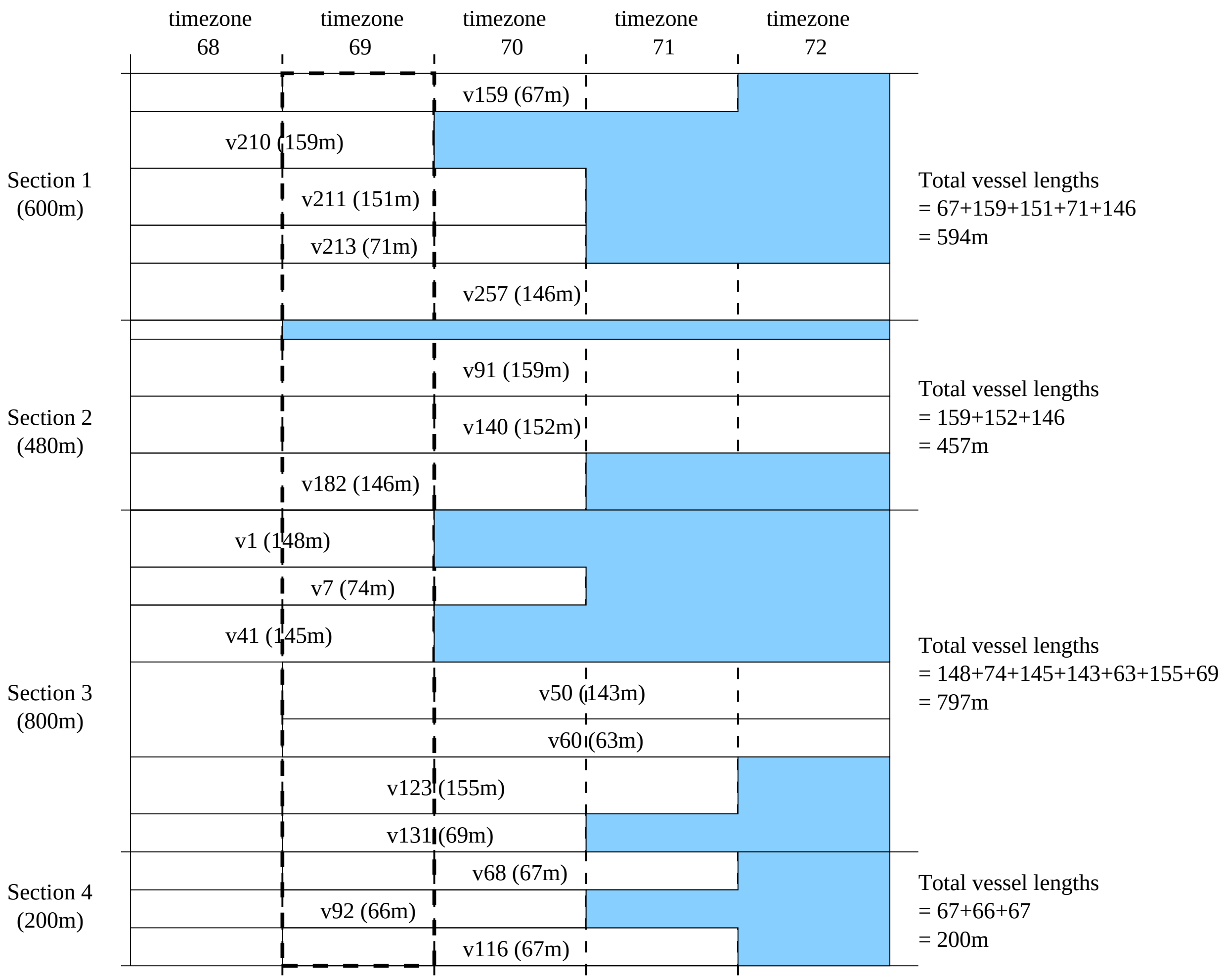

Figure 5.3: Partial Solution for d200 by BAP-BB

5.5 Further Work

Ideally we would like to compare our BAP-GP algorithm with the performance of other graph partitioning algorithms mentioned in Chapter 2. However, a straightforward comparison is not meaningful as BAP-GP is a generalisation of the graph partitioning algorithm to work with the BAP. Thus, in order to perform a meaningful comparison, we would have to adapt and generalise each of the other algorithms to the BAP. It is not immediately obvious how this should be done as the generalisation of the other algorithms is a non-trivial process requiring further research. This is beyond the scope of this Master's thesis. It could be studied as part of a further research work on the BAP.