Pumping Allocation at a New Zealand Oil Refinery

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Abstract

The Marsden Point Oil Refinery is owned and operated by the New Zealand Refining Company. The plant receives crude oil and refines it. One of the main operations is blending materials from component tanks into a final product tank. A decision tool has been created to determine which pumps should be assigned to which tanks, in order to minimise the blending time for materials at the Marsden Point Oil Refinery. This is subject to constraints on which pumps can be used for which tanks and how fast the pumps can operate.

Presently the pump allocation is performed manually where each operator has their own heuristic, which they apply to achieve the objective of minimising the blend time. Although these methods may work, they are not consistent and may not always achieve the optimal result.

The decision tool, which has been designed, gathers information such as what materials are in which tanks, the volumes of the tanks and the viscosity of the tanks from the existing spreadsheet. This information is put into a formulation for a mixed integer program. Then the formulation is solved using solver in Microsoft Excel. The information about the pump to tank combinations is collected and pasted into the existing spreadsheet for the operator to see the final allocations of the pumps, the final flow rates for the pumps and the final time taken to empty the tanks.

1.0 Introduction

1.1 Background on the Marsden Point Refinery

The New Zealand Refining Company owns and operates the Marsden Point Oil Refinery. The refinery is located at the entrance to the Whangarei Harbour in Northland, New Zealand.

The Marsden Point site was chosen because of its accessible harbour providing easy access for international shipments and was close considered the close to the main markets. At the time there was no history of seismic disturbance. It also had the deep berthing requirements for the large 100 000 tonne-plus takers that were expected to arrive, along with a solid shore and ample resources Marsden Point met the necessary requirements for a refinery[1].

The Marsden Point Refinery was officially opened on May 24th 1964 [3].

The main process that occurs at the refinery, is a process where the crude oil is shipped in from overseas, places such as the Middle East. The oil is then refined into products such as diesel and petrol. From this point the product is either shipped overseas to small nations, such as the Pacific Islands or distributed around the rest of the country.

After refining, distribution of petroleum products like petrol, aviation fuel and diesel occurs via a pipeline; it runs from the refinery down to the Wiri Oil Terminal in South Auckland, one of the major New Zealand cities. The pipe runs adjacent with the main road. From the Wiri terminal the petroleum products are distributed to the remainder of the country[2].

1.2 Background to the pump allocation problem

The final step in the production process is to blend several materials from component tanks to a product tank, in the minimum time possible. There are several pumps available to pump from the component tanks to the product tank. The product is then tested, if it meets the quality requirements, it can then be sent away.

Since a portion of the final product is shipped overseas, it is important to have the final product ready to be taken away as soon as the oil tankers arrive.
If the final product is not ready and the tide goes out before the tankers leave, demurrage occurs. This means the tankers have to wait for the tide to come back in before the tankers can leave.

The company incurs a penalty fee for not having the product ready, a fee is charged for every 24 hours the tankers have to wait.

Each day, two to three product tanks are blended. The refinery operates 24 hours a day. Information about what is in the component tanks and the volumes of the tanks are given half an hour before the commencement of the blend.

Time has to be allocated for the process itself, as well as the testing of the quality of the product after the blend. For the final product tank certain requirements have to be met. Requirements such as the product must have a certain amount of sulphur content and a certain density. If these requirements are not met then the product has to be modified. Quality standards have to be met in the blending process before the final product can be sent away, so time is a determining factor in the process, if tankers are waiting. Time is only critical 20 percent of the time.

At the refinery the allocation of the pumps is presently done manually by operators.

There are four different shifts that cover a 24-hour period, seven days a week. During this time there are 3 - 4 different people who perform the task of allocation. Each person has their own heuristic method for allocation, however they all have the same objective, of minimising the time taken.

2.0 Pump Allocation

2.1 Conditions of Pump Allocation

There are eight pumps with different flow rates available to pump from ten possible component tanks to a final product tank. Not all the component tanks are used. In most blends, the number of component tanks range from three to seven.

For some of the blends, not all the pumps are available; there may be a blend already occurring. Therefore, certain pumps are unavailable. Each pump can only be assigned once and all available pumps needs to be used.

For this particular problem, the blend process is considered independent from the refining process. Each blend and the subsequent allocation of the pumps are independent. Although the pumps may be used in other blends, other blends do not affect the final outcome of the blend allocation. Once the allocation of the pumps have been made the pumps can not be changed during the blend, this is ensure the quality of the materials flowing through the pumps.

There is a constraint on which pumps can be connected to which tanks, and which materials can be pumped by which pumps. This constraint exists because there may be physical limitations on the connection of certain pumps to certain tanks. This problem involves very large tanks that cover a large area, connection of a tank with a pump, which are located hundreds of metres apart may not be possible. Moreover certain pumps may not be able to handle certain materials because of the chemical make-up of the material.

2.2 Decision Tool

To solve the problem of minimising the blend time, a decision tool has been created as part of a fourth year project for an Engineering Science degree.

The decision tool is in the form of a Microsoft Excel spreadsheet with an accompanying program written in Visual Basic for Applications that links with an existing spreadsheet at the refinery. It contains a large amount of information about the blend and the chemical make up of each component material, before and after the blend process. There is also a formulation for a diet problem, which solves for a minimum cost of materials used while still meeting the requirements of the final product.

The decision tool works by an operator clicking on a button on the blend sheet labelled solve. The blend sheet is located on the existing spreadsheet, it contains the input data needed to complete the blend process.

Input data of what is contained in which tanks, what are the volumes of each material, what pumps are available and the viscosity of each material is gathered. This information is then used to set up a formulation for a mixed integer problem. Using Microsoft Excel Solver, an optimal solution is obtained in a matter of seconds running on a 350MHz Pentium II Processor.

The information which is output on the main blend sheet are the pump to tank combinations, the estimated time taken to empty each tank and the flow rates associated with each pump.

Currently the decision tool is being implemented at the New Zealand Refining Company by Geoffrey Gill, an Operations Research analyst who initially suggested the pump allocation problem.

2.3 Mixed Integer Program

To solve the problem of determining the pump assignment, a mixed integer program was formulated, that minimised the time required to blend component tanks.

For this pump allocation problem the following areas were identified:

Goal: to minimise the time to complete the blend.

Decisions: the allocation of which pumps to connect to which tanks.

Constraints: (1) Certain pump to tank combinations are not allowed
(2) All pumps have to be allocated to no more than one tank.

The areas identified are represented as integer variables and non-integer variables.

Integer Decision Variables: $x_{ij} = \begin{cases} 1 \text{ if pump i is assigned to tank j} \\ 0 \text{ otherwise} \end{cases}$

where i > j

Constraints: (1) $x_{ij} \leq 0$ For combinations of tank j to pump i not allowed

(2) $\sum_j x_{ij} \leq 1$ For each pump i to be used no more than once

(3) $0 \leq x_{ij} \leq 1$ each variable is an integer

For this problem, the goal is that the overall process time has to be minimised. In this process, the pumps are started at the same time, but empty at different times. The overall blend process time is associated with the tank, which takes the longest time to empty; this is the time that has to be minimised.

The following was formulated for the objective function, where ***T*** is the time to empty the tank, which takes the longest time to empty and T_j is the time it takes to empty tank j:

$\mathbf{T} = \max_j \{T_j\}$ *minimise **T** (minimise the maximum time)*

Given the fixed information, the volume of tank j, V_j and the flow rates of pump i connected to tank j, f_{ij}, the time is taken to empty tank j is:

$$T_j = \frac{V_j}{\sum_j f_{ij} x_{ij}}$$

The goal is to minimise the largest value of **T**, therefore:

Minimise **T**

$$T \geq T_1$$
$$T \geq T_2$$
$$\vdots$$
$$T \geq T_j$$

In order to solve this problem the objective function must be linear, **T** as it is, is non-linear, the reciprocal of **T** provides a linear objective function.

Minimising **T** is the same as maximising **1/T**, therefore the formulated objective function is:

maximise R *(where 1/* ***T****=R)*

subject to $R \leq R_j$

$$R_j = \frac{\sum_j f_{ij} x_{ij}}{V_j}$$

where R_j is 1/T for tank j
f_{ij}, is the flow rate if pump i is connected to tank j
V_j is the volume of tank j

2.4 Application to Excel

Once the formulation is devised it was then applied to a software package. For this problem Microsoft Excel 97, was used in the creation of the decision tool and Excel Solver was used to find an optimal solution.

3.0 Comparison with the Manual Heuristic

The manual heuristic that was used for the comparison is one method, which gives a feasible solution quickly. This method avoids allocation of the wrong pump to the first tank, therefore, leaving no available pump to pump the last tank, due to restrictions on the combinations.

For each tank, the number of pumps available to pump the tank divides the volume. The largest tank, with not many pumps available for connection is allocated to the fastest pump possible for that tank. This is done in succession until you reach the smallest and usually most flexible tank. The unallocated tanks are allocated to the tank, which is taking the longest to empty.

The following is a simple example of how this manual heuristic works.

Example 1: For this problem the pumps are assumed to be all available for use.

No. of pumps available for the tank	Tanks	Materials	Volumes	"New" Volume
3	43	AHGO	1058	1058/3=353

5	51	HCGO	2142	2142/5=428
3	49	VGO	356	119
4	53	BLGO	545	136
3	52	KERO	356	119

Table 1: A Simple Example

Using information about which pumps can be connected to which tanks, shown in Table 2, pump to tank allocations were made.

Pumps	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Flow Rates	140	300	320	200	120	340	150	500
AHGO	1		1				1	
HCGO		1	1	1		1		1
VGO	1	1			1			
BLGO	1	1		1		1		
KERO	1			1	1			

Table 2: Allowable Allocations

These allocations result in the following time approximations, of how long the tanks will take to empty:

Allocations:
T51 – Pump 8 (500m3/hr) – 4.3 hrs
T43 – Pump 3 (320m3/hr) – 3.3 hrs
T53 – Pump 6 (340m3/hr) – 1.6 hrs
T49 – Pump 2 (300m3/hr) – 1.2 hrs
T52 – Pump 4 (200m3/hr) – 1.8 hrs

In order to allocate the remaining pumps, the times were calculated to see which tank is taking the longest. Then the remaining pumps would normally be allocated to the tank, which takes the longest to empty, but for this problem no more pumps can be allocated. This simple example shows the flaw in using the manual heuristic. For tank 51 all the possible pumps, which can be used, have already been allocated, this means the blend time can not be improved by the use of the remaining tanks.

The following information is of an actual blend that was completed at the refinery, with the actual blend times for each tank, shown in Table 3. The allocations were completed using the manual heuristic discussed earlier.

Heuristic Allocation
NZRC Pump Line Up

Pumps	**Tanks**	**Volume**	**Flow Rate**	**Time**
1175	T52	775*	140	6.2
1179	T47	1000	300	3.7
1508	T43	3736	320	13.0

1180	T52	1108*	200	6.2
1506	T44	975*	120	9.0
1507	T53	3331	340	10.9
1182	T44	1219*	150	9.0
1196	T50	1168	500	2.6

Table 3: Heuristic Allocation

Using the decision tool to find an optimal allocation, the following was found, with the times being calculated from the given flow rates, shown in Table 4.

Decision Tool Allocation
NZRC Pump Line Up

Pumps	**Tanks**	**Volume**	**Flow Rate**	**Time**
1175	T52	1018	140	7.2
1179	T47	1000	300	3.3
1508	T44	2194	200	11.0
1180	T52	865	120	7.2
1506	T53	3331	340	9.8
1507	Not used	Not used	150	Not used
1182	T50	1168	500	2.3
1196	T43	3736	320	11.7

Table 4: Decision Tool Allocation

From the two sets of results, it can be observed that the Decision Tool provided a solution that is better than the manual heuristic, 13 hours for the heuristic blend and 11.7 hours for the optimal blend. Although the difference is approximately an hour, for the 20 percent of the time, the blend time is crucial; it is beneficial to be more accurate. Notice pump 1507 has not been allocated as it does not make a difference to the minimum pumping time as it can not allocated to the pump which takes the longest to empty.

4.0 Extensions

4.1 Changing Flow Rates

Once the decision tool was working with the fixed flow rates values, it was modified to include changing flow rates according to the viscosity of the materials passing through the pumps. This was done to improve the decision tool's solution and predicted times.

For the original formulation, the flow rates for each pump were the maximum values that the pumps could possibly operate at.

The flow rate formula is an approximation formulated by Geoffrey Gill.

Maximum flow for each material = (1+ c(3 –Visco_cs)^3)*maximum flow for each pump.

“c” is a tuning coefficient and is approximated to 0.005.
Visco_cs is the viscosity of the material, obtained from the input blend sheet.

Through the formulation of changing flow rates, it was observed that the very inviscid materials (Visco_cs > 3) seem to travel faster than the maximum flow rate for the pump. This means that the values of maximum flow are not really maximum flow rates, but average flow rates. The value of 3 must be an average viscosity of the component materials, as materials with viscosity less than 3 are slower than the maximum flow rates.

TIME TO EMPTY TANKS, hrs	**TIME TO EMPTY** TANKS, hrs
7.2423	7.0263
3.3333	3.3335
11.675	11.742
10.97	11.955
7.2423	7.0263
9.7971	9.7969
#N/A	#N/A
2.336	2.4769
11.675	11.955

Table 5: Comparison of Changing Flow Rates with Fixed Flow Rates

From Table 5, it can be seen that the overall and individual blend times do change when using changing flow rates. Most blend times do not change significantly, although very viscous or very inviscid materials can make a significant difference, if it is the maximum time. In this example the times change to the extent that the tank which took the longest in the fixed flow rates situation, changes in the changing flow rate situation. Overall the blend time does not change much, in this example the difference is 0.3 of an hour. Therefore in the situations where the deciding material (i.e. tank which takes the longest time to empty) is a very viscous or very inviscid material using flow rates dependent on viscosity is the better option.

4.2 Formulation of Diet Problem and Pump Problem together

Another possible way to reduce the time to pump the materials of the component tanks is to look at the product itself. By changing the mix of components, the blend time could be reduced, while still meeting the requirements of the product. The possible problem associated with changing the blend is that the cost on the blend may increase.
A linear program has been formulated to determine the optimal mix of materials from component tanks to produce a final product. This linear program assumes certain costs on the product.

The linear program is formulated as a diet problem. The objective is to minimise the cost to provide the final blended product, subject to the quality requirements of the final product still being met.

The Sulphur, Viscosity, Cloud point, CFPP and Cetane levels in the final product have to be within a certain range within the final product.

By combining the pump allocation problem with the diet problem, to form a super linear program formulation a better solution could be obtained.

The super formulation's main objective function is to minimise the cost of the blend materials, subject to the following constraints:

- That the requirements of the blend are met (sulphur, cetane, etc.).
- The requirements of the pump allocation problem are met.
- Time to complete the blend process <= an upper bound (the time remaining before the product has to be ready).

The aim of combining the two linear program is to see the correlation between the time to complete the blend and the cost of the blend.

Through experimentation, by trying a different mix of component materials, the time to blend can be reduced, while still meeting the requirements of the final product. A different mix of components would result in a greater cost.

By graphically comparing the different mixtures, time against cost, a frontier could be produced.

Ideally, the frontier would show that as the minimum time decreases, the cost would increase.

References

[1] C. Gaffney, B. Molloy, and G. Minchin, *On Stream 21st Anniversary*, First Edition, 1985.

[2] Ministry of Energy, *Natural Gas and Petroleum Products Pipelines through Urban Auckland: Information Handbook*, 1983.

[3] R. Trimmer, *The Story of the Refinery Port Facilities at Marsden Point and Whangarei*, First Edition, Northland Harbour Board, 1971.