Strategic Production Plan Model for the Hunua Quarry

Oliver L. Tompkins
Department of Engineering Science
University of Auckland
New Zealand
olivert@ihug.co.nz

Abstract

In early 2004 Winstone Aggregates approached the University of Auckland about developing a strategic model for decision planning at their largest quarry. The main pit at the Hunua Quarry has only seven to tens years of operational life left, and the development of an adjacent pit at Symonds Hill is being investigated. Winstone Aggregates wanted a long term model to assist with evaluating the optimal way to handle the development and transition to the new pit. The development represents a significant capital commitment and brings with it associated uncertainties, this tool provides a basis with which to control some of the uncertainty.

The Strategic Model was developed in VBA and AMPL and is solved through a two stage process making use of the free solver, LPSOLVE. Each development scenario is evaluated and ranked based on NPV and a risk factor associated with the ability to handle short term variation. The model was verified with test data and has been implemented by Winstone Aggregates.

1 Overview

1.1 Problem Background

In early 2004 Winstone Aggregates approached the Engineering Science Department about developing a model to help with production decisions at their largest quarry, the Hunua Quarry. This approach was prompted because of depleting resources at the main Hunua Pit and the need to investigate when an adjacent pit, Symonds Hill, should be opened.

Aggregate products are the crushed rocks, gravel or sand produced by quarries (Winstone Aggregates, 2005). They are vital for the infrastructure of our cities and are used in the construction of roads, motorways, buildings, homes, and drainage and water treatment systems. With such a wide variety of uses, aggregate demand is high. Total aggregate protection in the Auckland Region is currently growing at a rate of 12% per annum and with the current economic boom and the recent increased investments in roading, projections are that this growth will continue (Ministry of Economic Development, 2005).

This increasing demand has placed pressure on the all the quarries in the Auckland region. Extraction per year, however, is capped by Resource Consents, and so to meet the current demand, most of the quarries are already running at, or near, their legal capacities.

In the Auckland region, Winstone Aggregates have a nearly fifty percent market share (Winstone Aggregates, 2005). The Hunua Quarry, a Greywacke quarry situated in the Hunua Ranges, is the company's largest quarry. However the main pit at this quarry now has only between seven and ten years of resources left and so Winstone Aggregates is investigating the opening of an adjacent pit which will secure the operation of the quarry for a further thirty years. Because of the pressure on supply in the Auckland region this development is not only financially important to Winstone Aggregates, but is also important to ensure an adequate aggregate supply for the region.

1.2 Quarry Development

Quarry Development in New Zealand is governed in part by the Resource Management Act 1991 (RMA). When planning the development of a new quarry, or the extension of an existing one, quarrying companies must ensure that all aspects of the proposed quarry meet the requirements of planning objectives, rules and guidelines set out in the RMA. The main objective of the RMA is to manage resources while:

> **Section 5 c)** Avoiding, remedying, or mitigating any adverse effects of activities on the environment.

The process of gaining the necessary consents can be long and exhaustive, and the onus, at all points, is on the quarrying company to provide detailed information on all aspects of the quarry. The outcome often places conditions on developments and it therefore contains a large degree of uncertainty. Any changes imposed on the development will affect the financial viability of continuing and need to be investigated.

1.3 Model Requirements

Winstone Aggregates wanted a model to help them investigate the financial and operational implications of major decisions. Two key issues were raised by them as being of particular importance:

- How should the Symonds Hill pit development be handled.
- How well will the quarry respond to future demand variations and, if required, how early do mitigating actions need to be taken.

To ensure the model would get continual use, it also needed to be simple to set up and operate, yet flexible enough to be continually updated for changing market conditions and/or legal circumstances.

Simultaneously with my work, a geological consultant was contracted by Winstone Aggregates to determine different ways in which the Symonds Hill Pit could be developed. His work focused on different contours or routes that could be taken through the pit, and also looked at different years in which it could be opened. The development options he produced make resource forecasts and the purpose of this model is to compare these development options to determine which the best is.

1.4 Model Type

My initial investigation into production planning in the aggregate industry suggested that it quite closely resembled a hierarchical production planning structure. A hierarchical structure for the analysis of a decision making process was first proposed by Robert N. Anthony (1965). He demonstrated that for an ongoing system the decision processes can be categorized into three distinct categories, with each one corresponding to different time horizons, and generally also to different levels of management. The requirements, and time frame of this model, clearly mark it as a strategic decision.

1.5 Related Work

Within the Department of Engineering Science at the University of Auckland, two previous production plan projects have been done for Winstone Aggregates. These were done by Mitchell (1997) and Elangasinghe (2001). Both of these projects, however, were tactical models whereas this project is a strategic model. For this reason, those works were only consulted for background information. No similar work within this area was found outside the University of Auckland.

Significant research has, however, looked into the usage of operational research techniques in the optimising of long term production scheduling for open pit mining. Mathematical programming is well suited to this problem (Hochbaum & Chen 2000, Ramazan, Dagdelen & Johnson 2005) and OR techniques have become common in commercial packages used for planning open pit mines. An aggregate quarry is one form of open pit mine.

Virtually all the research into this area has focused on high grade mineral extraction rather than on aggregate extraction. Aggregates are a commodity and production is not greatly affected by the market price which is fairly stable. Hence most of the research into operations research in open pit mining applications is not applicable for this problem.

2 Problem Description

2.1 Resource Forecasts

All rock in a quarry is graded into one of three quality categories based on the degree of weathering (break down due to exposure to the elements) that the rock has been subjected to. The more weathered the rock is the lower its quality. Rock in the Hunua Quarry is graded into blue for the highest quality, blue-brown for medium quality and brown for low quality.

To extract rock from a quarry, a pit is quarried along vertical faces which generally contain differing amounts of each of the three grades. It is not possible to extract just one rock quality as the whole face must be quarried at once. Towards the top of a pit the faces will generally contain more brown rock and as you move deeper into the pit, the proportion of blue rock increases.

This distribution means that, as the pit ages, the proportion of unweathered to weathered rock increases. The changing proportions make the move to a new pit problematic. As the old pit runs down, large amounts of high quality, blue rock are extracted, and then, when the new pit opens, large amounts of lower quality, brown rock are extracted. Winstone Aggregates need a constant supply of each of the three resource types. For this reason both pits will need to be quarried simultaneously for a period of time, this is expensive and so the crossover period needs to be minimised.

The actual proportions of each of the three qualities that are extracted from the quarry fluctuations significantly over the short term but remain fairly constant over the long term.

2.2 Processing

Once the rock has been quarried it is processed into end products. This processing is done by crushing the rock and screening it into size groupings. A large crushing machine crushes the rock from boulders into smaller particles. The crushed rock is then screened into different particle sizes and either re-crushed into smaller pieces, or processed in secondary plants (RJ Maxwell, 2005).

The Hunua Quarry produces over thirty five different products and these products are made by setting up the crushing and screening machines to run different production modes. The cost of running the plant is dependent on the production mode being used. This cost changes due to the number of people required to operate the plant, the wear and tear on the plant equipment and utility costs.

For the purposes of this strategic model the 35 products can be grouped into four product groupings: Concrete, Asphalt, GAP and Hardfill, where each grouping is defined by the proportions of each quality resource it requires. The usages of each product and the ideal proportions of the resources in them are summarised in Table 2.1.

Product	***Usage***	***Blue***	***Blue Brown***	***Brown***
Concrete	Construction	1	0	0
Asphalt	Road sealing, construction	0.22	0.78	0
GAP	Roading base course layer	0.15	0.85	0
Hardfill	Roading sub-base course layer, filler	0	0.08	0.92

Table 2.1: Product groupings description.

While each product grouping has defined ratios for each type of resource quality, these ratios are continually changed up and down, by small amounts, to ensure that all demands can be met from the fluctuating resource supply.

The ranges in which each product grouping should be produced have not been explicitly defined by Winstone Aggregates and they have primarily used this flexibility as a tool to handle supply variation. To work out the ideal, minimum and maximum percentage bands on the resource inputs for each product grouping I analysed historical production data and talked to Winstone Aggregate managers about what they felt were acceptable minimum and maximum bounds as well as what they thought to be the “perfect” resource usage.

2.3 Demand Forecasts

Because the demand comes predominantly from long term contracts, accurate forecasts can be made for the demands of the quarry. In most instances, these contracts are legally binding and therefore the quarry is essentially demand driven. The legally binding nature of the demands is the reason why Winstone Aggregates want to be able to investigate their ability to handle future variations in demand or supply.

2.4 Capital Requirements and Variable Operating Costs

Quarrying is a capital expensive process and the decision when to commit capital is the main strategic decision facing management. The capital costs can be roughly lumped into two groups: capital commitments that are fixed in time and must be made regardless of the strategic decisions made, and capital commitments which can be committed at varying times depending on how the quarry is developed.

The first group of capital costs, those fixed in time, have no bearing on the decision process for this model as they can not be altered. This capital, however, does have a significant impact on the cash flow of the quarry and so to ensure the model’s accuracy it is important to include them:

- **Plant Capital:** All capital required to maintain the processing plant. There is only one plant for the two pits so this is independent of which pit is being quarried.
- **Other Capital:** The operation and development of the quarry requires fixed capital injections for purposes which may not be covered in other categories. These capital injections can often occur suddenly and unexpectedly.

The second group of capital costs, those which are only required if a pit is being quarried, is the important group for the decision process. The point in time in which these costs will be committed will differ for each development option.

- **Operating Capital:** The physical process of extracting the rock from the ground is capital intensive. Expensive machinery must be purchased, or hired, and this machinery will have associated depreciation costs.
- **Consenting Costs:** The development and operation of a quarry is governed by the RMA (see § 1.2). Consents must be obtained before a pit can be developed.
- **Site development:** The development and quarrying of a pit requires large capital expenditure in site development. Roading and other infrastructure must be developed and maintained between the pit and the processing plants.

Forecasts for all of the required capital can be made accurately based on previous experience and have been done by Winstone Aggregates in an initial investigation into the viability of the Symonds Hill Pit.

In addition to the capital costs outlined above, the quarrying process has associated variable operating costs. These relate to both the extraction of the resource and the processing into end products.

The extraction cost per cubic metre will be different for the two pits, making these costs important in the decision process.

2.5 Price Forecasts

The market price for aggregate products can be estimated by using historical trends and other forecasting techniques. Because products have been aggregated into product groupings, an average price has been used for each grouping.

The actual pricing is not going to affect the decision of the model but, again, it will affect the accuracy of NPV calculated.

2.6 Information Required by Winstone Aggregates

In order to make the best decision about when to open Symonds Hill, Winstone Aggregates wanted to be able to investigate the financial implications of different options. This information is important to them because of the long lead time required when making this decision and also for dealing with set backs that may result from the resource consent process.

The most important factor in evaluating the financial implications for all possible quarrying scenarios is, “can it meet all required demands?” For the scenarios that can meet all of the demands, the NPV of each scenario provides a way of evaluating the financial implications of committing the development capital at differing times and provides a basis for comparing each scenario.

The Net Present Value is a simple accounting technique that calculates the total value of the quarry taking into account the time value of money.

The formula for the NPV is:

$$NPV = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t}$$

Where C is the net cash flow in period t and i is the internal rate of return.

A secondary consideration for Winstone Aggregates when evaluating each development scenario is, under each scenario, how well the quarry will be able to handle variations in demand or supply.

To determine this, the amount of deviation away from the ideal that is required in the proportions of each resource grade for each product, can be viewed as the degree of risk inherent in each scenario. The more deviation required implies that the quarry is being stretched closer to its operational limits and therefore, there is less flexibility left to deal with short term demand or supply fluctuations. There is a greater risk that the quarry will become infeasible at some point in time. An ability to quantify this risk and to compare it among different scenarios helps Winstone Aggregates make prudent strategic decisions.

3 Model Formulation

The key piece of information that Winstone Aggregates must be able to get from the model is - which development scenario provides the best financial return? To answer this, multiple scenarios must be evaluated to ensure that they are feasible, meet all demands, and for those that do, the optimal development scenario is the one with the best NPV.

The second piece of information that must evaluated is - within each year, what proportions of each resource should be used in each product? For feasible scenarios, this information can be used to develop a risk profile, while for infeasible scenarios, it can be used to analyse where mitigating actions need to be made to achieve feasibility. For this decision, constraints are put in place on the allowable ranges of each resource for each product and a solution that minimises the deviation away from the ideal resource proportions described above is deemed the best solution.

3.1 Approach

To formulated the model as a two stage model solving for the NPV and feasibility in Visual Basic for Applications (VBA) and solving for the quality deviations in AMPL. This method was chosen as it provided significant advantages in both the simplicity of the model and also in the amount of information that could be taken from the model.

By splitting the problem into the two stage process using VBA and AMPL, I was able to avoid binary and nonlinear constraints and the size of the problem was reduced significantly. This simplified the model enough so that it solved very quickly using the free solver, LPSOLVE, and it also ensured that, when expanded, the model grew linearly.

3.2 Model Structure

The first stage of the model is primarily concerned with checking the feasibility of development options and then solving for the deviations away from the ideal proportions that are required in order to meet all demands. The second stage calculates the NPV for all feasible data sets and ranks the feasible data sets accordingly.

The feasibility is checked in VBA. This is done as the information is needed to determine whether to solve for the entire scenario data set or to only solve for part of it. If a scenario is feasible on every year then the entire data set is deemed feasible and the data set is passed onto AMPL. If a scenario is not feasible during any year then the scenario is deemed infeasible and all years up to the infeasibility are passed to AMPL to be solved. This is allows trends to be analysed.

3.3 Approximations

In formulating the model it was necessary to make certain approximations. Two that warrant specific explanation are: firstly, stockpiling constraints are ignored; and secondly, resource surpluses are discarded between years. These approximations decoupled the model between each year and significantly reduced the complexity of the problem.

Because of the long term nature of the model it was acceptable to ignore stockpiling. Stockpiling is a short term technique used tactically to allow the rate of production to remain consistent when demand oscillates, and to allow for production modes to run for longer thereby reducing downtime. The ability to meet the demands in this model, however, is considered on a yearly basis in the model, therefore the demand fluctuations do not need to be considered and it is acceptable to ignore stockpiling.

The discarding of resource surpluses has a greater impact on the accuracy of the model and, if not monitored, could potentially result in skewed results. Calculated surpluses are discarded for two reasons. Firstly, surpluses can not be rolled over year to year as this will result in resource forecasts that can not be physically achieved. Secondly, when considering technical aspects of the model, not rolling the surpluses over decouples the problem by removing linkages between the years. This makes the model significantly simpler to solve.

3.4 AMPL Model

The linear programme model formulated in AMPL is solved for each scenario in each year to find the best possible resource proportion mix for the final products. Deviation costs are assigned to force deviations away from the ideal proportions to occur first in the lower grade resource and in the lower value products; this is what is done currently by Winstone Aggregate quarry managers.

The model was formulated as a production planning model with the decision variable being the resource allocation for each product. The objective function was chosen to minimise the deviations away from a defined ideal and the constraints ensure that all demands are satisfied and that resource proportion deviations remain within the specified upper and lower bounds.

Indices
i = resources: Blue, BlueBrown, Brown.
j = products: Concrete, Asphalt, GAP, Hardfill.
k = time period: $S,\ldots, E$.

Parameters
S = first year of the solve period.
E = *last year of the solve period.*
C_{ij} = *cost of deviating away from the ideal proportion of resource i in product j.*
R_{ik} = *amount of resource i available in time period k.*

Djk = *demand of product j in time period k.*
Iij = *ideal proportion of resource i in product j.*
$Mnij$ = *minimum proportion of resource i in product j.*
$Mxij$ = *maximum proportion of resource i in product j.*

Decision variables

z_{ij} = surplus resource i in time period k.
d^{+}_{ijk} = deviation of resource i in product j and time period k away from the ideal proportion towards the maximum bound.
d^{-}_{ijk} = deviation of resource i in product j and time period k away from the ideal proportion towards the minimum bound.

Production Plan Model

1) Minimise $\sum^{3}_{i=1} \sum^{4}_{j=1} \sum^{E}_{k=S} C_{ij} (d^{+}_{ijk} + d^{-}_{ijk})_j$.
2) $I_{ij} + d^{+}_{ijk} - d^{-}_{ijk} \geq Mn_{ij}$ for all i, j, k.
3) $I_{ij} + d^{+}_{ijk} - d^{-}_{ijk} \leq Mx_{ij}$ for all i, j, k.
4) $\sum^{3}_{i=1} [x_{i,j} + d^{+}_{ijk} - d^{-}_{ijk}] = 1$ for all j, k.
5) $\sum^{4}_{j=1} D_{jk} [x_{i,j} + d^{+}_{ijk} - d^{-}_{ijk}] + z_{ij} = R_{ik}$ for all i, k.
6) $x_{i,j}, d^{+}_{ijk}, d^{-}_{ijk} \geq 0$.

Explanation

1) The objective is to minimise the total deviation cost to get the best resource allocation.
2) The proportion of each resource in each product must be greater than the minimum allowable.
3) The proportion of each resource in each product must be less than the maximum allowable.
4) The proportions of the resources in each product must total 1 for consistency.
5) The total product supplied to the market plus the surplus must be equal to the total resource available.
6) All variables are positive.

The C_{ij} costs were choosen to force deviations to occur firstly in the lower quality, lower value products. The relative costs used in the model were found, in consultation with Winstone Aggregates, through observation of what produced the most desirable allocation of the resources. Deviations in either direction away from the ideal were penalised equally.

3.5 Risk Assessment

The output from the AMPL model was used to develop a risk profile for each scenario. This is important information for the evaluation of each scenario, as the higher the required deviations are, the closer to its operational limit the quarry will have to operate at. The risk profile therefore shows the ability the quarry has to absorb short term variations and/or set backs.

To display this information in a concise and simple to interpret way, a risk count was calculated. For each scenario, a count is made of the number of year, product, and resource triples in which the deviation is more than fifty percent of the maximum. The size of this count between different resource scenarios represents the relative risk difference between each scenario.

The standard and average deviations for each product resource pair are also calculated and displayed as a percentage of the allowable deviations. This information can be used for further investigation into the risk associated with each scenario.

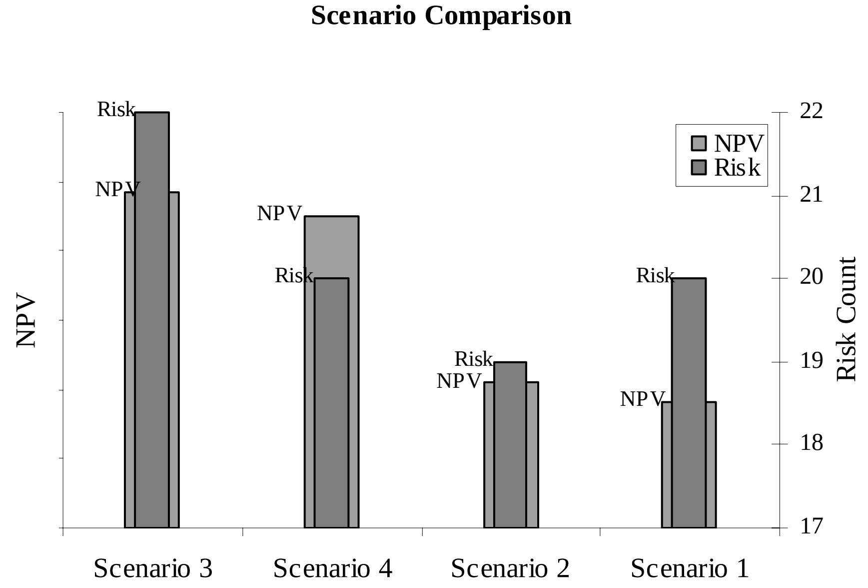

Figure 3.1: Results summary chart produced automatically by the model. The NPV values are blacked out for commercial confidentiality.

4 Implementation

A key issue that I identified early on in this project was the need to make the model very simple to use. For a tool such as this to have lasting usefulness it must be possible for any person with a reasonable understanding of the quarrying process to be able to set up the model and evaluate the results. To achieve this, two issues needed addressing:

- The interface needed to be simple and easy to navigate.
- The interface needed to be simple and not time consuming to set up.

To achieve both these goals I choose to use an Excel workbook and based its layout on spreadsheets provided to me by Winstone Aggregates. I split the workbook into six input sheets, one corresponding to each of the physical components of the problem (§2), and one results sheet and a results chart. At Winstone Aggregates' request, I also highlighted in a consistent colour all cells where the user is required to input data. This significantly increased the ease of use.

5 Model Validation

The purpose of developing this model was to provide Winstone Aggregates with a tool which they could use in an ongoing manner to continually undertake long term planning for the Hunua Quarry. To validate the model I formulated five resource forecasts, each based on different development options. I formulated these in such a way that the correct NPV ranking was obvious and I used all the demand, price, cost and capital data provided to me by Winstone Aggregates. Each forecast runs the Hunua Pit resource down at a different rate and opens the Symonds Hill Pit at a different time and at a different quarrying rate.

When the model was solved using the test resource data sets, the results produced were as expected. This validated the accuracy of the model.

A summary of the results with the NPV expressed as percentage of scenario 1 is presented below in Table 5.1. Because of the scale of the quarry operation, small percentage increases represent significant increases in value.

Scenario Name	***Symonds Hill Open Year***	***NPV***	***Risk Count***	***Rank***
Scenario 1	2009	100.00%	20	4
Scenario 2	2010	100.17%	19	3
Scenario 3	2011	101.78%	22	1
Scenario 4	2011	101.58%	18	2
Scenario 5	2012	-	No	-

Table 5.1: Validation results.

6 Conclusions

A strategic model was developed for Winstone Aggregates to model the long term performance of the Hunua Quarry. The model provides an accurate representation of both the physical quarrying operations and the capital commitments required for this operation and in doing this, it provides Winstone Aggregates with detailed information on the long term performance of the Quarry.

The model gives Winstone Aggregates a flexible, easy to use tool, with which they can investigate both of the key issues raised by them, namely:

- When should Symonds Hill Pit be opened and at what rate should quarrying begin.
- How will the quarry respond to future demand variations, and when should any mitigating actions begin.

To address these issues it investigates any required number of different quarrying scenarios and provides the following information for each one:

- The NPV of the quarry
- The required deviations from ideal resource proportions for each product and a risk profile derived from these deviations

To ensure the accuracy and flexibility of the model, all parameter information is controlled by Winstone Aggregates and can be changed by them at any point in time. This ensures the model is of continuing use.

Winstone Aggregates have implemented the model and have begun using as an integral part of their long term planning.

6.1 Limitations

The model was developed for use as a Strategic Production Plan Model and is intended for the long term planning of the Quarry development. It is not intended to be used for short or intermediate term planning.

The model has been highly aggregated into just four product groupings and necessary approximations were made. These simplification steps are necessary for the development of a long term model as they focus attention towards the important long term decisions, however, it is important that this is understood and that the model does not get used as a substitute for current tactical and operational planning procedures. It would be preferable if complementary optimisation models dealing with the short and intermediate time frame decisions were developed in the near future.

7 Acknowledgments

I would like to thank Dr Stuart Mitchell and Dr. Cameron Walker, my project supervisors, for all the help and guidance they provided to me through this project. I would also like to thank Winstone Aggregates for the opportunity to work on such a project, and for the time they spent gathering information and discussing the problem with me. My special thanks to Bernie Chote, Georgia Manning and Mark Rippey.

8 References

Anthony, R. N. 1965. “Planning and Control Systems: A Framework for Analysis.” *Harvard Business School.*

Elangasinghe, M. 2001. *Development of Strategic Planning Software at Winstone Aggregates.* University of Auckland Engineering Science Fourth Year Project.

Hochbaum, D. S., Chen, A. 2000. “Performance analysis and best implementation of old and new algorithms for the open-pit mining problem.” *Operations Research.* 48 (6) 894-914.

Mitchell, S. 1997. *Optimal Production Planning At Winstone Aggregates.* University of Auckland Engineering Science Fourth Year Project.

New Zealand Minerals, Ministry of Economic Development. 25 August 2005. www.crownminerals.govt.nz/minerals/facts/2003/region.html.

Quarrying Process and Quarrying Products, RJ Maxwell. 3 September 2005. www.rjmaxwell.com/education.

Ramazan, S., Dagdelen, K. and Johnson, T. B. 2005. “Fundamental tree algorithm in optimising production scheduling for open pit mine design”. *Mining Technology (Trans. Inst. Min. Metall. A).* 114 45-54.

Resource Management Act 1991, New Zealand Government. 19 September 2005. www.legislation.govt.nz/

Winstone Aggregates. Between 20 April 2005 and 25 August 2005. www.winstoneaggregates.co.nz.