The Missing Link

or

How to start your project out in the right direction and
ensure that it remains on course to reach your objective.

Introduction

We all recognise the importance of the early phase of a project, when the objective is being defined and the course set for a path to reach that objective. The further we progress down this chosen path, the more difficult and costly it becomes to make a change to the direction in which we are headed, so we want to get it right from the start. However, the objective is most often expressed in terms of business parameters, whereas the physical entity that is being developed in order to satisfy the business objective - the system - is defined in terms of engineering parameters, so that there is the potential for a disconnect between the two views of the project. This is illustrated in Figure 1, and the potential gap between the two views is what we call The Missing Link.

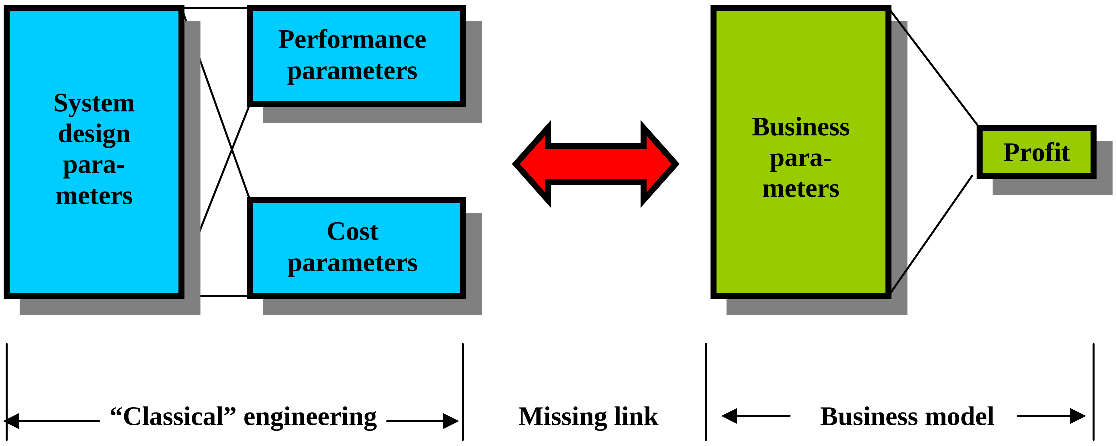

Figure 1. The link between the engineering and the business worlds.

One way to ensure that there is no disconnect between engineering and business is to make the relationship explicit in the form of a *model*, which expresses the business objectives in terms of engineering parameters. In such a model, the cost information is identical for the engineering and the business view of the project and requires no translation or modeling; it is the performance that is viewed differently and that needs to be linked, and this is done by introducing the concept of the *value* of the output produced by the system. On the one hand, the value is expressed as a function of the system performance parameters, on the other hand the value is defined so as to provide the revenue information required in order to calculate a business perfprmance parameter, such as profit or Return on Investment. Such a model has a couple of additional benefits – it is a very convenient tool for studying the effects of any change in either the direction of the engineering solution or in external circumstances (e.g. market or financing), and it provides an auditable trail of the decision-making process as the project develops.

An Example

In order to illustrate the steps involved in developing such models, we shall use a simplified industrial project – the ore handling system in an underground copper mine.

The purpose of the ore handling system is to deliver ore to the stockpile at the concentrator at such a rate that the stockpile is never completely depleted, i.e. so that the concentrator can always operate at its rated capacity. That is, in this case the client or market is the concentrator.

The main functional elements of the ore handling system are illustrated very schematically in Figure 2; they are extraction, crushing, underground conveying, loading, hoisting, and surface conveying.

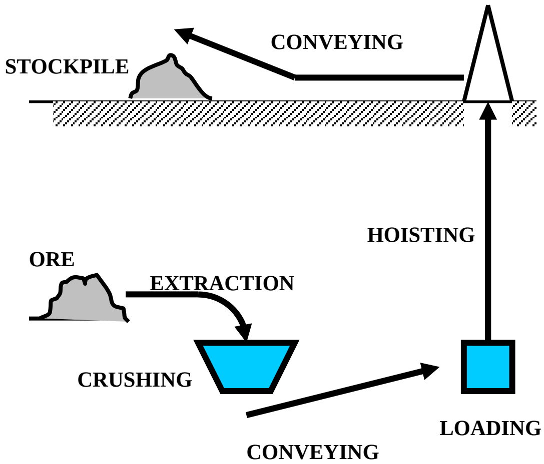

Figure 2. The main functional elements of the ore handling system

However, in addition to these main elements, there is the whole infrastructure, consisting of power, water, dewatering, ventilation, control and communications, maintenance facilities, and construction support facilities.

Some of the early design options that could be investigated by using such a model to determine thir business implications include:

a. The number of crushers - one or two. Two crushers, even though each might be smaller than a single one, is still much more expensive, but offers a number of operational benefits.

b. The use of a grizzly/rockbreaker combination in front of the crusher or not. A grizzly is a heavy rectangular screen that only passes ore less than a certain size; larger rocks remain lying on top of the grizzly and have to be reduced in size by a rockbreaker in order to be able to pass through. Using a grizzly/rockbreaker combination in front of the crusher reduces the size of the crusher.

c. Inserting some storage capacity in front of the loading element or not. Due to its high cost, the hoisting system is the functional element which limits the capacity of the ore handling system. Therefore, it is important to utilise the hoisting system to its full capacity, and not let it be idle due to a temporary breakdown of one of the processes providing ore to it. A storage bin provides a buffer.

Of these, we shall look at b. in some detail, once we have described the framework and its application and indicated how it would be tailored to the ore handling system.

Developing the Model

The development of a model that links project parameters with the business objective involves a number of distinct steps. The details of each step, as well as the effort involved, will vary from case to case, but in general the issues that need to be addressed in each step are the ones outlined in the following sections.

1 Develop the Value Function

1.1 Define the Output

The output is the product or service that is required in order to reach the business objective. It is characterised by the *volume* of the output and by the *quality* of the output, and in this model framework the volume is treated as a *boundary condition.* That is, it is predefined as part of the business objective, e.g. as a production program, delivery target, or market demand forecast.

Ore Handling: In this case, the product is essentially a service – the transport of the ore from the draw point to the concentrator stockpile. The concentrator requires a steady flow of ore, 24 hours per day, 365 days per year, of 750 tons per hour, and the stockpile has an effective capacity of 15,000 tons.

1.2 Identify Output Parameters

The output parameters are the *n* parameters that are significant in defining the quality of the output, and thereby the *value* of the output, as discussed in the next subsection, and they are usually determined by the users (or the market). In a given case, the value of the output may be affected by a vast number of parameters, but most of these have only a small influence on the value and can be ignored at this stage of the design process, and the model framework limits the number of output parameters to six.

Ore Handling: The only parameter is *deficiency* of ore at the concentrator, measured e.g. as the number of hours, K, of forced (non-scheduled) down-time of the concentrator per year due to a lack of ore. There is a penalty attached to any forced downtime (which is therefore effectively a reduction in value of the output); but otherwise the ore handling system cannot alter the value of the ore in any way. This penalty is determined by factors outside this model, and turns out to be $20,000 per hour.

1.3 Estimate Influence Factors

The value is generally what the users pay (or would be willing to pay) for a unit of the output. The influence of each output parameter on the value can vary both in type and in magnitude. The type is one of two, either *additive* or *multiplicative*, and the magnitude is determined by the value of an amplitude, w(i). However, the influence is not normally an on/off affair; it is generally true that the dependence of the value of the output on a parameter is such that below a certain minimum parameter value, u(i), the parameter has no influence, and above a certain parameter value, v(i), the influence saturates. Therefore, if we introduce a function f(I;*x*) defined on the domain $0 \leq x \leq 1$ by

$x \leq u(i)$: $f(I;x) = 0$

$u(i) < x < v(i)$: $f(I;x) = x/v(i)$

$x \geq v(i)$: $f(I;x) = 1$;

then, for the case of m multiplicative and n additive parmeters, the value function W(x) can be defined as

$$W(x) = \prod_{i=1}^{m} w(i) f(i;x)(1 + \sum_{i=m+1}^{m+n} w(i) f(i,x)) \ .$$

Ore Handling: The case of the ore handling system will allow us to demonstrate a couple of issues involved in using this predefined form of the value function. There is only one parameter, the deficiency, K, so m = 1 and n = 0, but the value decreases with increasing x, so in order to fit into the above form, we have to transform the variable according to x = (1-K/8760), assuming the accounting period is a year. The value of w is the (largely arbitrary) internal target transfer price, which is set at $4.50 per ton. The value of v is 1, and the value of u is determined by the value of x at which the deficiency reduces the output value to zero, given by 1 - 4.5·750/20,000 = 0.804.

2 Develop the System Design Parameters

2.1 Identify the Functional Elements

In order to produce the output, the system must be able to *do* a number of things, such as convert, transport, store, etc. (*How* it does it and, above all, what it must *be* in order to do it is not at first a concern; that will be introduced when we start to use the model as a design tool.) Each of these things is represented by a *functional element*, and these are linked together in a particular *structure* in order to produce the output. The structure is usually represented in the form of a block diagram, and this framework basically allows only four different structures:

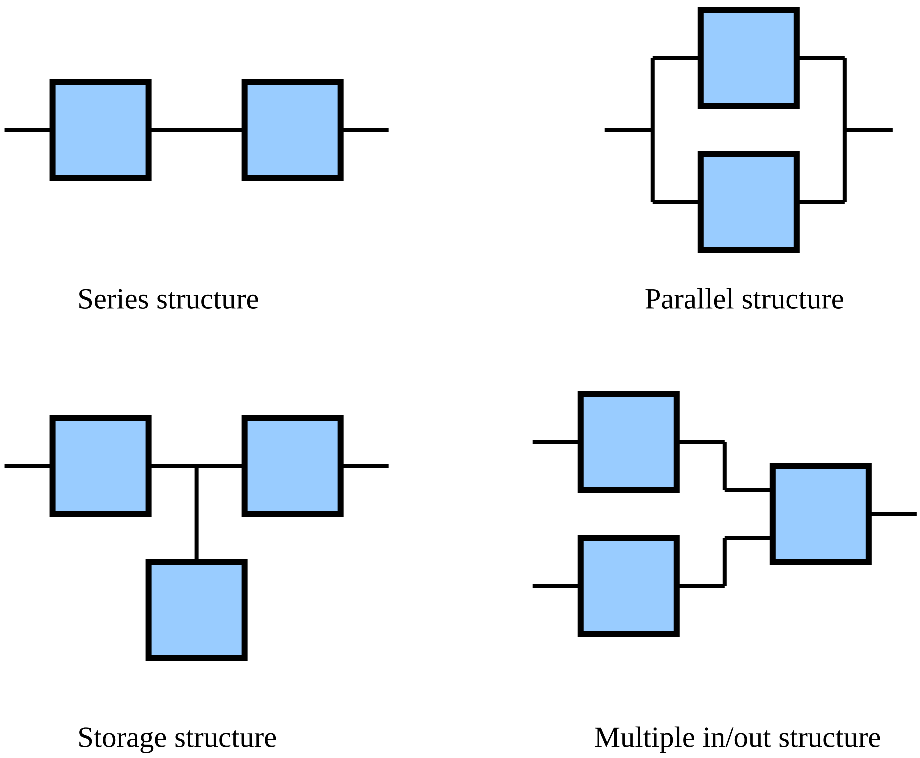

Figure 3. The four basic model structures.

Ore Handling: There are the six functional elements indicated in Figure 2, plus the storage in front of the loading element:

1 Extraction
2 Crushing
3 Underground conveying
4 Storage
5 Loading
6 Hoisting
7 Surface conveying

The six functional elements from Fig.2 are linked together in *series*, i.e. for each element the input rate equals the output rate of the preceding element, and the output rate equals the input rate, as there is no storage. (In reality there is a small amount of storage in chutes and bins, but that is ignored in this simplified model.) However, between elemnts 3 and 5 there is the storage element. Thus, the block diagram is relatively simple:

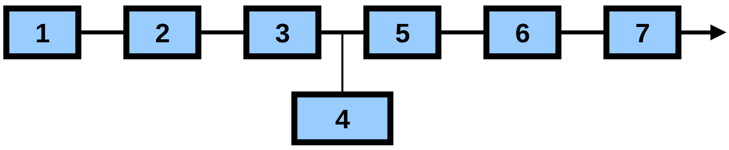

Figure 4. Structure of the ore handling system model.

There is only one thing to note about this diagram - there is no input, i.e. no dependence on an external source; we are assuming that there is always an abundance of ore to be extracted.

2.2 Determine Cost and Performance Variables

With each functional element are associated a number of cost and performance variables. As the elements are purely functional and have no physical form, the cost variables must be understood as target values, based on experience and market intelligence. The performance variables will be linked to the output parameters through the functional structure.

The cost variables are the same for each element in all projects;

1 Capital Cost
  11 Design and Development
  12 Procurement
  13 Construction
  14 Testing and Commissioning
2 Operating Cost
  21 Personnel
  22 Consumables
  23 Raw Materials
3 Maintenance Cost
  31 Corrective Maintenance
  32 Preventive Maintenance

33 Adaptive Maintenance
4 Decommissioning Cost
41 Decommissioning

For any particular project, it is necessary to define what is included in each of these cost variables.

At this point we need to consider the time frame of the project. We shall simplify the life sycle of the project by describing it in terms of two phases only - the development phase, and the operating phase, both of which are measured in *accounting periods.* The former encopasses design, procurement, construction, and testing and commissioning; the latter includes all upgrades and refurbishments. The duration of the decommissioning phase is not a separate variable; decommissioning is assumed to take place in the accounting period following the end of the operating phase.

The performance variables may vary somewhat from element to element, but are generally some form of the following five variables:

Capacity (storage capacity, production rate, throughput capacity, lifting capacity, etc.)
Quality (meeting one or more specified parameter values)
Reliability (usually expressed as Mean Time Between Failures, MTBF)
Maintainability (usually expressed by two variables - Mean Time To Repair, MTTR, and Scheduled Maintenance Downtime [in hours/accounting period])

In the case of the reliability, we are assuming that failures occur at random and at a constant rate, resulting in an exponential failure density function. In the case of repair times, a more realistic assumption is the following triangular repair time density function:

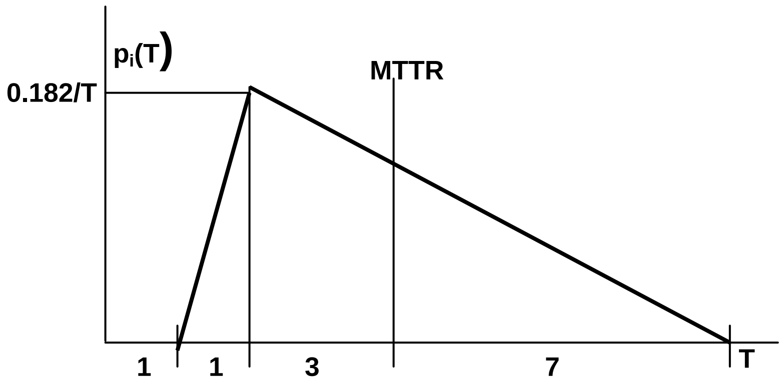

Figure 5. Repair time distribution, with unit of time = MTTR/5 .

2.3 Identify the Design Parameters

The values of the cost and performance variables associated with the functional elements are determined by a set of *design parameters.* These are the parameters that the design engineer can change, and at this stage we are looking at only very high-level or global design parameters, such as the choice of technology or choice of location, as well as parameters related to the project execution, such as contracting strategy and financing options. They take on only certain values, limited by experience, market availability, etc. Also, the project parameter values may be linked, i.e. a certain choice for one parameter dictates or limits the choice for another parameter, so that project parameters are generally expressed as *scenarios*, consistent sets of project parameter values.

Ore Handling: As already indicated, we shall consider only three project parameters - the number of crushers (1 or 2), grizzly/rockbreaker (yes or no), and storage capacity (yes or no). That is, each parameter represents a choice for the realisation of a functional element. However, for all three elements there is an associated continuous variable - the throughput of the crusher, the opening of the grizzly, and the capacity of the storage, and it is an intrinsic assumption that for each choice this parameter has been optimised. We shall return to this issue in the chapter *Using the Model*.

3 Develop the Executable Model

3.1 The Model Framework

3.1.1 Overview

The model framework consists of a number of Excel spreadsheets and associated VisualBasic for Applications (VBA) program modules. The choice of Excel as the user interface rather than VB forms is based on the fact that Excel is available on most PCs whereas VB is not, and on the desire to allow the user access to the program itself, which would not be the case if the model were supplied already compiled into machine language.

There is a Main sheet which contains information about the program (Client's name, project name, version, etc.), controls the running of the program, accepts some of the overall project parameters, and presents the output in the form of the total debt requirement and the ROI.. Then there is one sheet for each functional element that accepts the values of cost and performance parameters as input, and a Performance sheet that accepts the value function as input and calculates the system performance by linking the performance of the elements.

The sheeets all have a fixed (i.e. non-project specific) header and footer, and a three-line application-specific title block, which identifies the Client, the project, and the particular application, with version and date. As an example, the ten sheets for the Ore Handling model is shown in Appendix A.

3.1.2 The Main Sheet

The purpose of the Main sheet is to define the model as a whole. That is, a description of the model in relation to the system being modeled, the global model parameters, the number of elements, and the structure of the model.

The VB module associated with the Main sheet contains a number of procedures. Two of these procedures - the subroutines *Developmenmt Funds* and *Operations* - constitute the financial model. This model will not be a completely accurate representation of the financing arrangements for every project, but it provides a compromise between accuracy and detail that is appropriate for the initial stages of a project as far as an evaluation of such financial measures as Return on Investment (ROI) is concerned. And as far as the application of the model to design optimisation, the details of the financing have little influence, as we are only considering changes to the cost-benefit, and not absolute values.

The financial model is based on the following two definitions:

> *The Present Value, PV, of any monetary entitiy (cost or revenue) shall be the value of the monies involved, discounted to the point in time when the systems goes operational; that is, when it starts to produce its service.*
>
> *The Return on Investment, ROI, shall be that percentage of the equity that, when subtracted from the revenue in every year of the operating lifetime of the system, results in a Net PV, NPV, of zero for the project by the time the system has been decommissioned.*

The financial model relies on the following five assumptions:

(a) The equity is paid in full at the start of the project.
(b) The equity partners will forgo any return on their investment until the start of the operating phase, but will then withdraw the return every year during the operating phase. Thus, the return on the equity can be treated as an operating expense.
(c) The equity is paid back to the investors at the end of the operating phase so that, after decommissioning costs have been paid, the project capital is reduced to zero (as required by the definition of the ROI.
(d) The equity is not less than the development cost, and the debt facility will not be used before the equity has been fully expended. Until the equity is expended, the remaining part earns interest at 0.8 times the discount rate.
(e) Interest on the debt is paid every accounting period, but repayment is only carried out during the operating phase. The repayment is by means of a fixed sum per accounting period.

In order to calculate the ROI, the financial model goes throught the following steps:

1. Determines the total cost and revenue in each accounting period, excluding financing costs, by reading and summing the values contained in the Element and Value sheets.
2. Determines the expenditure of the equity and the interest on the remaining equity in each accounting period, and determine the accounting period in which the equity is expended.
3. Calculates the total debt at the end of the development phase, and the resulting repayment and interest in each accounting period in the operating phase.
4. Calculates the total ernings, expresses this as a sum of equal payments, and determines the ROI by dividing by the equity.

3.1.3 The Element Sheet

To each functional element there is one Element sheet; they are created by making copies of the master element sheet contained in the model framework. The Element sheet contains a description of the element, the element parameter values, and the various costs in the two project phases, plus the decommissioning cost.

Some element parameters are prescribed in the master sheet; they are MTBF, MTTR, and Scheduled Downtime. Additional parameters (e.g. those characterising the functionality) must be defined in the description and their values listed in the Parameter section.

3.1.4 The Output Sheet

The Output sheet combines the performances of the individual elements according to the model structure (as defined in Step 2.1), and calculates the system output (as defined in Steps 1.1 and 1.2). The definition of the system output and the associated output parameters is entered on the sheet for reference, and each output parameter is assigned a position in the output table.a The framework allows up to (and including) six output parameters. The VB module associated with this sheet contains the procedures required to calulate the output as a function of the performance of the individual elements, and developing this program constitutes a major part of the work involved in creating the model (i.e. in tailoring the framework to a specific case).

While the system output is characterised by only a few parameters as far as its value is concerned (i.e. as the output is perceived by the "market"), linking it to the element performances requires us to make assumptions about a number of other parameters; these are the *model parameters*, and their values have to be entered on the Output sheet.

3.1.5 The Value Sheet

The first information that needs to be entered on the Value sheet is a short description of how the value of the output is defined. The formal definition is then entered by assigning the output parameters to either the multiplicative or additive category, and giving values to the three parameters that define how the each output parmeter influences the value or the output. The value of each output parameter is read from the Output sheet.

The total value of the output in each accounting period is calculated by multiplying the value per unit output by the volume, as predefined as part of the business objective and entered in the Volume column on the Value sheet.

3.2 Tailoring the Framework

3.2.1 Overview

Given the framework described above, we then have to develop an executable model for the particular case of interest. The process is somewhat akin to developing a fault tree, where one starts with a system failure mode and then finds the hierarchy of subsystem and component faults that would cause this failure mode. Here we start with one of the output parameters, and then determine what element characteristics influence this parameter. We then develop the optimisation algoritms, as mentioned in Sec. 2.3, and finally determine the value function parameters. The whole process is best explained by showing how it is done in a particular case, and again we use the ore handling system as our example.

3.2.2 The Output

There are only two parameters, the rate of supply (i.e. the long-term average) and the deficiency of ore to the concentrator, the parameter denoted by K in Sec.1.2. Considering the latter one first, a deficiency will occur whenever the ore supply (to the concentrator stockpile) fails for a period longer than the time it takes to deplete the stockpile, or 15,000/750 = 20 hours. From the structure of the model, as shown in Sec.2.1, it is clear that this will occur if any of the three elements 1, 2, and 3 fails for more than 20 + C/750 hours, where C is the capacity of the storage element or if any of the three elements 5,6, and 7 fails for more than 20 hours. Given the distribution of repair times defined in Sec.2.2, it is straight forward to show that the average number of hours of failure in excess of T hours per accounting period, k, contributed by an element with given MTTR and failure rate, λ, is given by the expression

$$
\begin{aligned}
k &= \lambda \cdot MTTR \cdot \kappa(\vartheta), \text{ where} \\
\kappa &= 1 \text{ for } \vartheta < 0.2 \\
&= 1 - 0.091(\vartheta - 0.2)^2 \quad \text{for } 0.2 \le \vartheta < 0.4 \\
&= -0.303\vartheta^2 + 0.364\vartheta + 0.873 \text{ for } 0.4 \le \vartheta < 2.4 \\
&= 0 \text{ for } \vartheta \ge 2.4 \text{ ,}
\end{aligned}
$$

and where θ is the normalised value of T for that element, or T/MTTR. The total number of hours for the whole system, K, is the sum of *k* for the six elements.

3.2.3 The Value

The value function is determined by the three parameters, *u*, *v*, and *w* for each output parameter. These are chosen to reflect the opinion of the users (or Client, or market) as well as possible. In the case of the ore handling system, they were determined in Sec. 1.3.

3.3 Validating the Model

Once completed, the model is validated, firstly, by running it for a particular system design for which the outcome is known, usually from manual computations, and verifying that it produces the correct result. Secondly, the output function is validated by verifying that it reacts appropriately to changes in the system parameters.

Using the Model

Let us recall the purpose of constructing this type of model - it serves as a link between the engineering parameters and the business parameters. That is, given a particular engineering solution to meeting the user requirements, we can see what the business outcome of accepting this solution would be and, perhaps more importantly, given a contemplated change to the design, the model will show the effect of this change on the business outcome. However, it is important to recognise that the model does not determine or suggest what that solution or change should be; that remains the task of the design engineer.

There are two issues that must be understood and taken into consideration in using the model, and the first of these is that the framework will, in principle, support a wide range as far as the level of detail is concerned, and that a specific model needs to be targeted at the level of detail appropriate to the stage of the design process under consideration. For example, in the case of the ore handling system, we were in the early stages of the system design, but prior to that, there would have been a higher level model in which the functional elements were e.g. ore production, concentration, and shipping, and where the users would have been the world market for concentrate, and it would have been this model that determined the value of such parameters as the production target (i.e. 750 tph) and the cost of unavailability of ore at the concentrator (i.e. $20,000 per hour). And in the later design stages, there might be more detailed models developed and added on for each of the functional elements in the ore handling system model.

The second issue is that when we use the model to investigate or compare different design options, each option needs to be “consistent” and “internally” optimised. To illustrate what we mean by “consistency”, take the case of the capacity of the ore handling system. The rate of supply of ore, Q, measured in tons per hour, is determined by first considering the effect of scheduled maintenance on the ore handling system. The scheduled shutdowns lead to a *design availability*, A_0, which is less than 1, so that the *nominal production rate,* Q_0, equals 750/A_0 tph. However, the actual production rate is less than the nominal rate because of unscheduled breakdowns (random failures), and for the subsystem consisting of the three elements following the storage, i.e. elements 5, 6, and 7, we can calculate an effective availability, A_b, as follows:

$$\Lambda_b = \sum_{i=5}^{7} \lambda_i \ ,$$

$$MTTR_b = \frac{1}{\Lambda_b} \sum_{i=5}^{7} \lambda_i MTTR_i \ ,$$

$$A_b = \frac{1}{1 + \Lambda_b MTTR_b} \ .$$

Consequently, the three elements in this subsystem need to be designed to have a transport rate of $Q_b = Q_0/A_b$.

For the subsystem consisting of the three elements 1, 2, and 3, the transport rate is determined by the requirement for being able to fill an empty storage within a time that is short compared to the expected time events that will require the storage to be drawn down. For various reasons this time was chosen as 24 hours, so that the transport rate is given by

$$Q_a = Q_0 \frac{18000 + C}{18000} \ .$$

Therefore, if we look at any design option, such as inserting storage in front of the loading function, we have to take into account that the transport rate for the elements 1, 2, and 3 also needs to be increased in order to take full advantage of the storage. Just looking at the cost of providing the storage and the benefit of having it would not be a “consistent” option.

The requirement for the options to be “optimised” is best illustrated by another example; in this case, the option of using a rockbreaker/grizzly combination ahead of the crusher or not. The starting point is the distribution of rock sizes as they are produced by the particular mining method, in this case block caving. The distribution is described by giving the percentage of ore that would pass though a grizzly (i.e. a giant sieve) with square openings of side length l, E(l), and because the size of the bucket on the load-haul-dump (LHD) front-end loaders used in the extraction process effectively limits the linear size of rocks presented to the crushing element by the extraction element to about 2 metres, $0 < l < 2$ m, with E(0) = 0 and E(2) = 1. For conveneience, we shall assume that the form of E(l) is given by $(l/2)^{1/n}$, where n is determined by matching this function to the actual (or predicted) distribution at l = 1 m. That is, n is given by the expression

$$n = \frac{\log(0.5)}{\log E(1)} \ .$$

A few values are:

E(1)	0.89	0.917	0.94	0.94
n	6	8	11	16

If the hourly rate of ore production is Q, then the hourly amount of ore, dQ, which would not pass l = L but would pass $l = L+dl$ is given by

$$dQ = \frac{Q}{n}\left(\frac{l}{2}\right)^{1/n-1} dl \ ,$$

and in this amount of ore, the average weight of a rock would be about L^3 tons. Therefore, the number of rocks per hour, N(L), that would have to be broken by the rockbreaker before they would pass through a grizzly with opening L is given by

$$N(L) = \frac{Q}{n2^{1/n-1}} \int_L^2 l^{1/n-4} dl$$
$$= \frac{Q}{(1-3n)2^{1/n-1}} \left[2^{1/n-3} - L^{1/n-3}\right]$$

For Q = 850 tph, the result is shown in Figure 6.

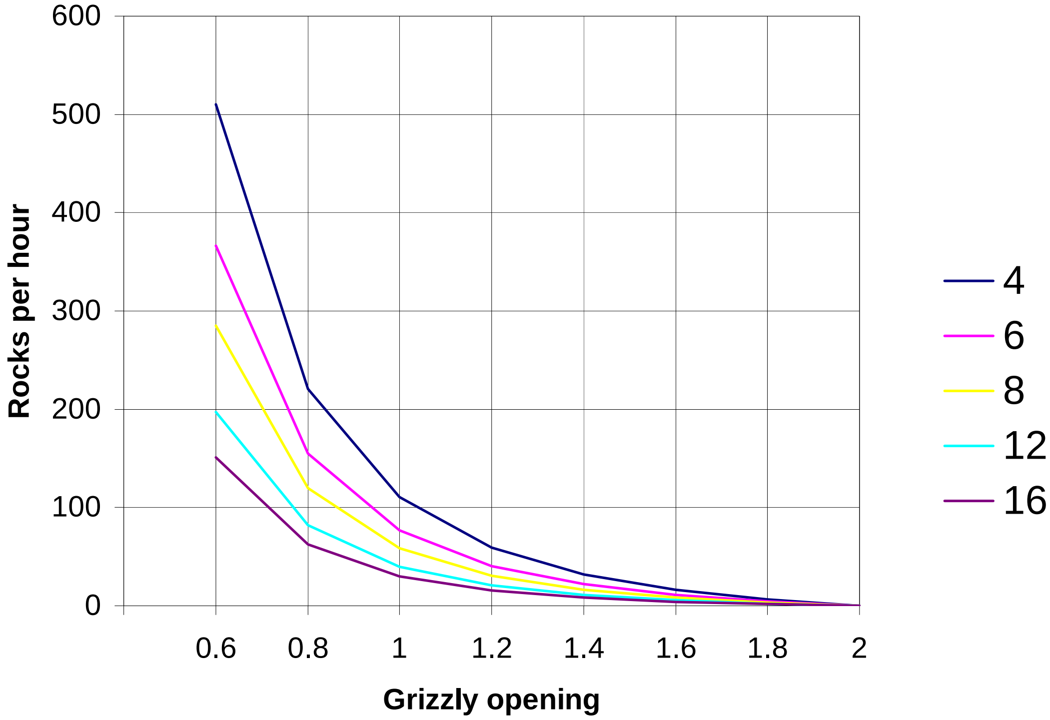

Figure 6 The number of rocks per hour that will not pass through a grizzly with a given opening (in metres), for a number of different rock size distributions (as determined by the parameter *n*) and a total ore throughput of 850 tpa.

Now, a rockbreaker operator can manage to break an average of about 100 rocks per hour, so depending on the rock size distribution (i.e. on the value of *n*), the optimum grizzly opening can be chosen using Fig. 6, and the associated crushing station components (plate feeder, crusher, crushing chamber, etc.) dimensioned accordingly. It is this grizzly/crusher combination that must be compared with the option of using a crusher large enough to accept the largest rocks (i.e. of 2 m linear size) directly.

Both of these examples should serve to demonstrate that while the model links the system design to the business outcome, determining consistent and optimised design options will, even at an early stage of the system design, involve considerable additional work and detailed insight into how the system functions.

Organisation of the Work

The work required to achieve the outcomes described in the previous section is naturally subdivided according to the steps defined there, but the organisation of the work must also take into account the differences in participants required for each step. Consequently, the work is normally carried out in the following fashion:

Briefing: The Client provides documentation and verbal briefing to the Consultant on the current status of the project. This allows the Consultant to prepare for the workshops.

Output Definition Workshop: The participants in this workshop are the ones that have a direct interest in the business outcome, i.e. corporate management, sales and marketing, and finance (as it relates to the market side). It is typically a half-day workshop, and the outcome is an agreed definition of the value function.

Project Workshop. The participants in this workshop include primarily the people who will determine how the project develops, i.e. project manager, design manager, and people involved in arranging the financing of the project. Again, this workshop will typically occupy half a day, and the outcome consists of:

a. A set of project parameters;
b. one or more scenarios (sets of project parameter values);
c. a set functional elements linked in a particular structure; and
d. the cost and performance variables describing each functional element.

Model Development. This is the main work package, and it is performed by the consultant using the framework outlined earlier. It typically involves about a week's work, and results in an executable program.

Model Verification and Delivery. In this last work package, the test scenario previously defined is used as input to the model, and the resulting value of the value function calculated. The data and results of this verification run for the (simplified) case of the ore handling system are shown on the sheets contained in Appendix A.