

# Optimization By Integrating Engineering and Business Models

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## ABSTRACT

To optimize is to find the “best” solution given certain conditions and constraints. What is meant by best and how to find it has received scant attention. To the engineer, “best” may be quickest, strongest, most reliable and so on. The engineer will have models to determine whether one solution or setpoint is better than another based on objectives such as these. “Best” in business is quite different. It means to maximize profit or minimize loss. The economist or accountant also has models. Note the obvious disconnect between the objectives of engineering and business models. This disconnect has hindered us from finding a practical best to improve profit on the plant floor. Simple questions like what is the best tension to run have no useful answers from a strictly engineering or business viewpoint.

This paper begins by defining best in several familiar contexts. The conclusion here is that the only “best” that makes sense in an industrial environment will minimize total costs. To find this best we must integrate engineering and business models. This technique developed here is very powerful, flexible and adaptable approach. The technique can be applied explicitly using calculus or similar numerical techniques when cost functions are well known. Even more flexible is an implicit approach when very little is known about costs. Five web handling examples are used to illustrate this problem solving technique. These examples include a variety of objectives such as optimum rejection levels, core waste, web tension, layon roller nip and water flow rate. These examples show how it is easy to combine apples and oranges, such as waste and delay, when one converts to a common denominator of cost.

## KEYWORDS

Optimization, cost, economics, waste, tension, nip, flow rate, customer, management, product design, process design.

## OPTIMIZATING DEFINED IN SCIENCE AND ENGINEERING

To optimize is to find the “best” solution given certain conditions and constraints. Varying a single condition will often result in a different “best”. Thus, the optimum firing angle for a projectile will change with the slightest movement of target location and velocity as well as wind speed or direction. What is “best” changes with the specifics of a problem. For example, the quarterback may target the end’s midsection if he is uncovered but may throw high to avoid a potential interception. The quarterback may even throw the ball away if he is rushed. “Best” may also incorporate more than one goal where each may conflict with the resources of the other. The ‘Great Taste or Less Filling’ advertisement suggests, quite accurately I might add, that it is difficult to make a beer that is both full-flavored and low-caloried.

Sometimes an optimum is well defined, usually by standards. We don’t debate that a second is 9,192,631,770 periods of certain radiation band of the cesium-133 atom. However, some standards are not so straightforward. While most agree that the A note above middle C has a frequency of 440 Hz, other notes are not as well defined as you might think. Though scientists give middle C a frequency of 262 Hz, most musicians ignore this. Depending on the type of scale (just intonation, equal temperament, mean tempered, American Standard or International Standard), Middle C may be as low as 256 Hz or as high as 278.4375 Hz. Harley-Davidson specified in 1975 that 3/8” bolts on their shovelhead motorcycles were to be torqued at 20 ft-lb for SAE 2 and 54 ft-lb for socket head cap screws. However, even this precise

single-valued optimum belies complexity. These optimums are the collective judgment and experience of mechanics and engineers who are trying to find the best spot between a rock (overstressing the bolt) and a hard spot (bolts or parts coming loose during service). The true optimum, as opposed to one of mere standard, depends on many factors not specified such as friction coefficients and the use of locking devices.

## **OPTIMIZATION IN BUSINESS**

“Best” in business is usually more straightforward. Optimum is quite simply to maximize profit or minimize loss. Here, the objective function is dollars. While one might argue the appropriate interest or inflation rate or whether to use present or future dollars, these are mere details. On the face of it, maximizing profit makes great cents. The purpose of business is to make money. True, there may appear to be non-monetary company goals as well, such as being good members of the community and being good stewards of the environment. These are but constraints that may change how much the optimum (profit) will be. For example, if we donate to local charities or use more expensive but environmentally friendly processes, optimums will take different values. However, what business calls optimum will not change. It is still called dollars.

It is interesting to observe that many management fads of late, such as Zero Defects and Six Sigma, may well conflict with the basic goal of business (2). In other words, trying to *achieve* zero defects would inevitably cause a company to go broke long before actually getting there. Moving *toward* zero defects may similarly mean moving toward bankruptcy. This commits the same error of thinking as the engineer who thinks stronger is better. Let’s take the semi-conductor industry as an example. They are currently at only about 1-2 sigma for chip yield (a sizable fraction of the chips are rejected internally). To decrease the internal waste an order of magnitude may well raise manufacturing costs so that the product might not be competitive. If not, two orders of magnitude would certainly do it and we still would not be anywhere near the goal of Six Sigma much less Zero Defects. While there may be many benefits to programs such as these, quite possibly even improved profit, they are incomplete for a very simple reason. Programs such as these are not built from the ground up based on economics. Instead, they are statistics based where at best economics are tacked on as something of an afterthought.

## **OPTIMIZATION DEFINED HERE**

Here, we recognize that the purpose of business is to make the most money subject to whatever constraints are imposed on us, whether they be legal, moral, environmental, availability of capital, the wishes of the CEO and so on. Thus, we must build our analysis from the ground up on an economic foundation, not tacked on afterwards in a decision making step. While business schools have taught this profit principle for a century, the practice has not reached the plant floor in a practical or useable fashion. While we know that web tension affects profitability, we don’t know how to find the economic optimum tension. The same could be said for many of the process parameters we deal with daily including nip loads, temperatures, flow rates and so on.

We will build this optimization technique by integrating engineering and business models. We will illustrate the technique by only optimizing one variable at a time. However, the principle can be extended to multiple variables optimized either simultaneously or sequentially and iteratively. We can use this optimization technique at two levels. One would be explicit when we have detailed cost information to work with. However, we can also use this implicitly where we know the factors involved and their approximate values and sensitivities. Before we proceed, however, let us review separately the use of optimization in engineering and mathematics with a familiar example.

## WARMUP OPTIMIZATION EXAMPLES FROM ENGINEERING

A well-known optimization problem is to maximize the distance traveled by a projectile. Here, one is constrained to a given projectile, environmental conditions and, most importantly, initial velocity. The only variable one can control is the trajectory angle. Obviously, pointing straight up is not the right answer because the projectile will have zero horizontal velocity. Similarly, pointing straight away is not right either because the projectile will have no time to travel horizontally before it strikes the ground. The answer must be somewhere in between straight up and straight away. We can derive the optimum firing angle for the simple case of no air resistance and high order effects as follows:

The horizontal and vertical components of initial velocity,  $v_0$ , are

$$1a) \quad v_{x0} = v_0 \cos \theta \quad \text{and}$$

$$1b) \quad v_{y0} = v_0 \sin \theta$$

The altitude of the projectile at any moment is

$$2) \quad y = y_0 + v_{y0}t + \frac{1}{2}a_y t^2$$

We can find the time to impact,  $t_i$ , by setting  $y_0 = 0$  and noting that  $a_y = -g$  so that

$$3) \quad 0 = v_{y0}t_i - \frac{1}{2}g t_i^2 \quad \text{so that}$$

$$4) \quad t_i = \frac{2v_{y0}}{g}$$

During that time, the projectile has traveled a distance to impact,  $d_i$ , where

$$5) \quad d_i = v_{x0}t_i$$

Solving for  $t_i$  in 5) and combining 4) we have

$$6) \quad \frac{d_i}{v_{x0}} = \frac{2v_{y0}}{g}$$

Inserting 1a) and 1b) into 6 and solving for  $d_i$  we have

$$7) \quad d_i = \frac{2v_0^2 \sin \theta \cos \theta}{g}$$

To find the optimum firing angle,  $\theta_{opt}$  we take the derivative of  $d_i$  with respect to  $\theta$  and set equal to zero we get the expected result of

$$8) \quad \tan \theta_{opt} = 1 \quad \text{or}$$

9)  $\theta_{opt} = 45^\circ$

To summarize the simple calculus, we write the equation for the dependent variable in terms of constants and an independent variable. We take the derivative and set it equal to zero. The places where the derivative are zero as well as the two endpoints are all candidates for minima and maxima. All candidates must be checked numerically to make sure that the correct candidate for minima is identified.

Figure 1 shows the range for various firing angles with this well known model. This, however, is academic analysis and is not very useful in the real world. Elevation differences, air resistance and other high order effects complicate analysis greatly. Table 1 shows results for some common projectiles using either modeling and/or measurements.

TABLE 1 – Optimum Firing Angle

Angle (Degrees)	Case
45	Projectile in a vacuum
35-40	Baseball
25-30	Golf ball
31	Paintball at maximum legal velocity
5-15	Golf disc (Frisbee™)

Note that the higher velocity paintball will benefit from a lower firing angle than the baseball to minimize its already considerable distance it must plow through the air. However, the golf ball appears to be an exception. That is because the spin imparted creates lift so that the ‘effective’ angle is, in effect, greater. The same is even more so for the Frisbee. Other complications include wind. If there is a headwind or crosswind, the best angle is reduced while a tailwind will make a slightly higher angle an advantage.

It is interesting to note that these optimization problems are seldom performed by calculation or measurement except in academic settings. In the real world, the ball player has no measure of angle, nor any measure of performance. The variable and the results are subjectively estimated. Nonetheless, a good ball player will sense within a degree or two the correct angle for any situation. They will know far before the ball hits the ground how close to the optimum they threw that time. This fine tuning of performance is done by thousands of repetitions.

Some parallels can be seen in the industrial setting where very nearly optimum answers have been obtained without formal analysis. Indeed, most settings in the plant are not far from their best. Operators and process engineers alike move knobs around and subjectively or formally analyze the results. The utility of the industrial optimization approach to be introduced shortly will tell you when you are not at your best and help you move toward a better “best.”

No matter how complicated cases such as the projectile travel problem get, we are still only using physical models and, more importantly, we are only optimizing one thing – distance traveled. Let’s take an even more important problem of the “best” fuel air mixture for a gasoline engine. The “best” from a theoretical viewpoint is the stoichiometric ratio of 1:14.6 by weight. At this ratio, every molecule of hydrocarbon is exactly matched by a molecule of oxygen so that there is no excess (unburned) fuel nor excess (unutilized) oxygen.

However, we can get different answers if we chose a different objective function. If, for example, we want to maximize engine power the mixture will be 10-14 depending on the conditions. However, if we want to maximize economy (kw of power per liter per second of fuel consumption), the optimum will be 16-19. What if our objective function was to minimize pollution? In this case, we need to run on the lean side of peak. What if maximum engine longevity was what we wanted most? In this case, we would have to run off peak, usually to the rich side, to keep the engine cool. More to the point, what if we wanted it all: good power, good economy and a clean long-lasting engine? Here, we would have to convert all of our desires to the same units and then apply optimization, but what units?

## EXAMPLE 1 – OPTIMUM REJECTION LEVEL IN Q/A

In the business world, there is only one objective function that makes any sense at all: maximizing profit or minimizing loss. This is why strictly engineering models are incomplete. If you want to increase the safety factor on the spars of an airplane wing,, you merely need to make them bigger. There are two big problems with this type of thinking, however. First, it makes the implicit assumption that stronger is safer. A quick review of aviation accidents will show that very few structural failures occur on wing spars. Moreover, most of these are avoidable if the pilot stays away from exceptionally violent storm clouds or getting into a spin when flying VFR into IFR conditions. One would get much better results by putting efforts in other areas. Here the weak link is much more often the pilot than the plane. Second, even granted that stronger is safer, we end up with a problem of every increasing spar size and weight until we have not enough engine left over to carry passengers once the heavy wing is lifted into the air.

This bigger is better fallacy has widespread acceptance in some segments of the business world as exemplified by Zero Defects, Six Sigma and other programs. The idea of reducing defects is certainly a good one to consider. However, taking it to extreme always gives the same result: bankruptcy as the cost of manufacturing soars with very little incremental gains in recovered waste or product value. Business economics has taught us that the maximum profit is obtained when the incremental costs match the incremental savings for a single given variable. The problem is applying these principles to the industrial world.

Let us take an example of setting the best amount of product to reject. This is a great example because it illustrates the problem with bigger is better thinking. We simplify by assuming, for this example only, that we reject on only one type of test. However, we do allow that the test imperfectly correlates to consumer acceptance or satisfaction. Our goal is to optimize (minimize) the total costs to produce. This includes manufacturing cost, rejected waste as well as consumer complaints or returns. The only thing we can adjust at this time is the rejection level. If we set it too tight, we reject perfectly good product and the effective costs to manufacture will increase. This is called supplier risk. If we set the criteria too loose, we pass on troubled product to the customer who then will complain. We will pay for customer service calls and back charges at the least. We may also need to increase marketing efforts and costs to replace lost customers at the worst. This is called customer risk. We must select the “best” fraction of the material to reject as a balance between supplier and customer risk. This fraction will translate readily into specific value for the test given the distribution. However, we need not do that here as the purpose is illustrating technique rather than details peculiar to a process.

Starting with costs to produce. If we reject half of the material, the costs to produce any salable unit will double. More generally, without getting unnecessarily fancy, we can let the costs to produce a salable item be

$$11) \quad C_m = \frac{k_m}{f}$$

where

$c_m$  = the cost to manufacture a salable unit

$k_m$  = the simple costs to manufacture a unit w/o considering rejection or customer complaints

$f$  = fraction of the manufactured product to be passed (i.e., not rejected internally)

We note that at the bounds, the costs to produce a salable unit are sensible. As  $f \rightarrow 0$ , the costs to produce a salable unit go to infinity as everything is rejected. Similarly, as  $f \rightarrow 1$ , the costs to produce a salable unit are the same as the cost to manufacture as nothing is rejected.

In a similar fashion we can model customer complaints. Here, however, we may need to get a bit more complicated in order to model the complexities of the human customer. First, we must note that customers may complain about things not related to the test. For example, if we reject on gage but the consumer is also interested in color, a base level of complaints will be inevitable. This seems so trivial that the reader will immediately say why not test and reject on color as well. The problem is that there will always be some cause for complaint that is either difficult to test for (e.g., bagginess) or impossible to test for (customer has a headache when your product is being run). It matters not whether the causes for dissatisfaction are real or perceived, justified or malicious, the results will be the same: rejection on untested or untestable parameters.

Another complication is that the cost of customer complaints is more, perhaps even far more, than merely crediting them for the returned material. There are many reasons for this. First, the simple credit does not take into account round trip transportation, the cost of service calls and complaint processing as well as other hidden costs. Second, customers do not reliably complain when they are unhappy. Thus, for every received complaint there may be 2 (expensive goods and services), 10 or even 1,000 (cheap commodity items) customers who were not happy but did not register a formal complaint. These customers may leave you in part for this unhappiness for which you have only a few warnings. This is insidious because it is nonconservative. The complaints you hear about and see are literally the tip of the iceberg. Lastly, you may need to increase advertising and marketing efforts to make up for the lost customer base.

We might capture some of these complications in a simple fashion as follows.

$$12) \quad c_c = k_{c1} + (k_{c2} - k_{c2} f^n)$$

where

$c_c$  = per manufactured unit costs of customer complaints

$k_{c1}$  = per manufactured unit cost factor for complaints not related to rejectable parameter

$k_{c2}$  = per manufactured unit cost factor for complaints related to rejectable parameter

$n$  = sensitivity of customer to rejectable parameter

$f$  = fraction of the manufactured product to be passed (i.e., not rejected internally)

Again we check some bounding conditions. If the customer is not at all sensitive to the rejectable parameter,  $n=0$ , then the costs are only those not related to rejectable parameter. However, if the customer is very sensitive the costs will skyrocket. An example might be from the medical industry where a few failures are a big deal.

We can now sum the total costs as,

$$13) \quad c_t = c_m + c_c = \frac{k_m}{f} + k_{c1} + k_{c2} - k_{c2} f^n$$

Taking the first derivative with respect to the fraction not rejected internally we have

$$14) \quad 0 = \frac{-k_m}{f^2} + n k_{c2} f^{n-1}$$

To solve for the “best” fraction  $f$ , we are going to need to select a sensitivity. Lets try  $n=2$  as a simple example. Then

$$15) \quad f_{optimum} = \sqrt[3]{\frac{k_m}{2k_{c2}}}$$

Checking the trends we note that the more expensive it is to produce the item,  $k_m$ , the less you want to reject. On the other hand, the more damaging customer unhappiness,  $k_{c2}$ , then the more you want to reject. For an infinitely fussy customer who can poison the market for your product, you want to reject virtually everything. We also note, with satisfaction, that factors not related to the test have no bearing on the optimum for that test.

There are obviously restrictions on the factors  $k$ , as there would be with any factors. The modeler is obligated to check results. If the model is analytical, then the restrictions can be checked explicitly. If the model is strictly numerical, the model should be pushed for reasonable values of the variables.

These costs are graphically displayed in Figure 2 below. We note that the costs to produce skyrocket as rejection approaches 100%. Similarly, customer complaints fall off as more and more of the troubled product is kept from them. Note that the optimum value is not at the intersection of the curves as many erroneously think. Rather, it is where the derivatives are equal but opposite. For this case, the optimum amount to reject internally is about 20%.

## EXAMPLE 2 – OPTIMUM CORE WASTE

One coated paper mill was trying to reduce what they called “stub losses,” which was the amount of paper left on the reel spool at the coater unwind. Here, as elsewhere in the paper industry, about 2” on the radius is the norm. However, each inch of material represents about \$1,000,000/yr in waste. Thus, going from a 2” stub to a 1” stub would save the paper mill a million dollars every year per machine. The rub, however, is that as the stub size is reduced, the break rate at the unwind increases. There are two reasons. First, for modest stub sizes we find that the material is damaged near the spool because of less than perfect starts as well as because the material at the spool has to support perhaps as much as 50 tons of paper above it under rotating Hertzian contact stresses. Second, for very small stub sizes there is an increasing chance of a ‘miss’ where the paper runs off before the turnup is made. The cost in any case is about ½ hour of downtime at \$20,000/hr on this wide high speed coater for every web break. This is a very interesting problem because we are simultaneously optimizing waste (stub losses at the core) and delay (web breaks). Using neutral but relevant objective functions allows us to analyze otherwise intractable ‘apples and oranges’ problems.

We again will use dollars as our objective function. With this example, the parameter we can control and wish to optimize is the material left on the core measured as inches on the radius. Let us start with the costs of material. There is no need to get fancy here as the cost is nearly proportional to stub size for any reasonable stub size. Thus,

$$16) \quad c_w = k_w r$$

where

$c_w$  = per annum cost of waste due to stub material left on core

$k_w$  = cost of stub waste per inch of radius per year

$r$  = stub radius (material left on core) in inches

The break rate is a bit more complicated because we seldom have good physical or empirical models. Nonetheless, we can proceed by noting a few constraints based on what we do know. First, the break rate will never be zero. There is a base rate of breaks that happen independently of position near the core. For example, the web may be damaged prior to winding such as during formation. Similarly, the web can quite easily break on the coater, especially the coating head, for reasons unrelated to the unwinding supply roll. Second, the break rate due to damage near the core and especially runoffs must go to infinity as the stub

radius goes to zero. Third, we know from experience that the break rate goes to the base rate of breaks (independent of radial position on unwind) at some distance above the core, call it  $r_0$ . This radius for many master and finished rolls is something on the order of 4 inches, but can be as high as a foot off of the spool. Thus,

$$17) \quad C_d = k_{d1} + \frac{k_{d2}}{r}$$

where

$c_d$  = per annum cost of delay due to web breaks  
 $k_{d1}$  = per annum cost of delay due to web breaks not related to position above core  
 $k_{d2}$  = per annum cost of delay due to web breaks related to position above core  
 $r$  = stub radius (material left on core) in inches

Adding waste and delay,

$$18) \quad C_t = k_w r + k_{d1} + \frac{k_{d2}}{r}$$

where

$c_t$  = per annum total cost of waste and delay

Taking the first derivative of cost with respect to radius and setting equal to zero

$$19) \quad 0 = k_w - k_{d2} r_{opt}^{-2}$$

and

$$20) \quad r_{opt} = \sqrt{\frac{k_{d2}}{k_w}}$$

where

$r_{opt}$  = optimum stub waste on radius

Figure 3 shows an example with  $k_w=1$ , which is well known, and  $k_{d2} = 2$ , which is an estimate. With this model, the optimum stub size is 1.4" allowing a savings of more than half million dollars per year per machine as a potential for merely revising a flying splice radius setting in the computer from its previous 2" setting. However, we must ask how confident we are in the model itself. The waste function is trivial and well known, but how about the delay function? Unless we actually have significant running time at different splice over radii, we would not know. It may take weeks of accumulated running time at each of several radii to get statistical significance and trustworthy model. In practice we would probably need to change radii randomly and keep track of breaks to reduce the influence of other variables, such as grade changes, on the results. If it turns out that  $k_{d2} = 4$ , then the optimum stub waste is 2", right where most are currently operating. Thus we must test the model and continue to retest the model as conditions change until we are sufficiently confident. Retesting will cost not only process engineering time, but also in waste/delay as we inevitably move off of our current best guess optimum, to find out how well things run elsewhere.

## IMPLICIT MODELING

I want to now move away from explicit modeling to implicit modeling. We have illustrated with two examples how cost models can, with perfect sense (cents), combine disparate goals. In the first example of optimum reject level, waste and customer complaints were combined. In the second example of core material, waste and delay we combined. We will leave it to the practitioner to devise their own models for their own optimization problem of interest. All we need is a trustworthy model, usually empirical, for the costs of any trouble as a function of something that can be changed. We are not limited to simply one waste cause. We simply add up all of the cost functions and minimize the sum.

However, it is not always easy to do this in practice. The explicit approach, just like many tools of the statistician, engineer or scientist, is data hungry. What happens if you don't have the data or it is impractical to obtain? One might be tempted to dismiss the tool as impractical in the real world. This, however, would be shortsighted as thinking that equations and numbers are needed to practice science. That is also not true. Equations tell us three things: which knobs to move, which direction to move them and how far to move them. Not having equations and numbers is not so limiting as you might think for applying science implicitly allows us to do two of the three: know which knobs to turn and which direction to turn them. Trial and error (experience) then tells about how far to turn the knobs. We will use this same philosophy for optimization by finding best when you don't have much data to work with. This way of thinking allows us to work on most problems, even if we only have a vague idea of only two costs rather than a confident model of two cost functions. Let me illustrate this philosophy with some example problems.

### EXAMPLE 3 – OPTIMUM TENSION

We begin by laying some necessary groundwork for implicit analysis. First, we assume that there *is* an optimum value, which in this case is tension, for any given situation. Second, that this optimum is determined, as before, by the minima of total cost. This is not so difficult to accept because the converse is that there is no optimum. In other words, it would make no difference where you turn the tension knob. Ample experience tells us that the converse makes no sense. Since we know tension does indeed make a difference, there must then be at least one optimum. Third, we assume that tension is neither good nor bad; but rather has both good and bad aspects at the same time. We will check this assumption later, but for now an explanation is in order. To do this we need a problem to work on.

Let's take a paper printing press as an example problem. Web tension is a good thing for the printing press because it stabilizes the web. More specifically, the more tension you run, the less impressions are rejected due to colors being out of register. This is indeed the experience of press operators world wide. That is not to say that you can eliminate misregister merely by tension because there are many other causes, both mechanical and control, that can compromise register. We are just assuming that for this specific problem tension is good for register. The goodness of tension is captured in Figure 4 as a decrease in lost impressions due to misregister as the tension is increased.

If this were all there were to the story, the optimum tension would be infinity. Since this is not reasonable, we know our model is not complete. (In fact, continuing to increase tension in this fashion will cause a different type of register problem when the web goes from flat to stretched long and narrow.) We also know that tension can be bad because it will increase the incidence of brittle web breaks as evidenced by scores of peer-reviewed papers and the experiences of a hundred thousand operators. (The analogous penalty for tension in film printing might be necking which causes rejection due to width or registration.) Again Figure 4 captures the relationship between costs and the parameter of concern, tension. For web breaks, high tension is clearly a bad thing. The rate increases faster than the 2<sup>nd</sup> power of tension depending on the system. If brittle web breaks were all we needed to consider, then the optimum tension would be zero. Obviously this purely brittle web break focus is also incomplete. Even the web break costs are incomplete if one only includes brittle breaks. As seen in the figure, very low tensions can cause a break of a different sort; the web wanders too far sideways and crashes into something. Thus, the web break cost curve is really the sum of two distinctly different troubles: low tension wandering breaks and high tension brittle web breaks. Note here too that breaks do not go to zero because there are other causes

not related to tension.

To complete the model, we must sum all of the good and bad aspects of tension as related to costs of manufacturing. In the previous examples, we simplify the problem by saying there is but one good and one bad aspect to the variable to be optimized. We can easily extend this to as many factors as we know about so the technique is itself not limited. The only limits are our knowledge about our manufacturing costs. Returning again to Figure 4, we see that there is some optimum tension where costs are minimized. It is not at the intersection of the two cost curves as many think. Instead, it is where the slopes are equal and opposite. Note that optimizing tension alone would not give a system optimum. Rather, the system minima of costs is at a slightly higher tension than the web break minima because of the benefits of tension on improving registration.

At this point it seems that we may be stuck because we drew this particular figure with complete lack of numerical data. We are only using the collective experience of the industry that lightweight paper tends to run best around 1 PLI tension and that web breaks and register are of similar costs. In the real world it is quite likely we would not have information detailed enough nor could we get it easily or cheaply. Trials, probably of weeks of duration, would be necessary to construct these curves explicitly. These trials would be expensive to run because some trials would cause higher waste levels. The discipline to run trials like this and to analyze the information properly are other limitations. However, we will use an implicit technique to see if we have 'about the right answer' for tension.

We note that for reasonably shaped cost curves the optimum is *near* where the curves intersect. We can make use of this in an incredibly simple fashion. All we need to do is to look up waste costs for the two issues considered, registration and web breaks. These costs are readily obtained in most plants. If we find the two troubles are way out of balance, then we know that we are probably not at the optimum. For example, if we ran 1 PLI (the low end of the design range for newsprint), Figure 4 shows that registration waste would be four times as much as web breaks. Both costs are readily obtained. This suggests that we should increase the tension setpoint even without having the benefit of the graph.

At this point we leave ourselves open to a couple criticisms. The operator will say that increasing tension will increase web breaks. She will be right and *she* will be the one to have to clean up more messes. She has already through years of practice found the tension that has the fewest breaks and you suggest a move that would increase breaks. However, as true of most industrial problems, the technical aspects are usually the easiest. It is the people aspects that can be much harder to work out. You must use all of your skills to sell or persuade the operator that yes breaks will increase a little bit, but the increase will be less than the improvements in the registration waste. The bottom line is that you must sell the *bottom* line. That is, in the end the company will be better off with this change in operating practice.

Second, management can easily become an obstacle to process improvement. They task you with reducing *both* registration and web breaks and you come back by saying that we will be in better health by having both defects. Trading one defect for another is not going to be an easy sell, even if all you ask for is a trial long enough to demonstrate whether economic gains can be made. Yet the analysis shows that if you don't like the resulting answer, i.e., best is not good enough, then you can't get any better by moving the tension knob. Tension in that case is set as best as it can be. Instead, you will have to move a curve. This in practice usually means a redesign of product or process. For example, if we increase the weight of the paper, breaks and registration should both improve. The other objection will be one of the pitfall of the 'home run.' Here, management seldom gets excited about small gains. They tend to think more along the lines of all or none when it comes to setting goals. Yet, that incremental, evolutionary, continuous improvement is the mainstay of process improvement rather than the revolutionary advance. Baseball is like this too. Home runs are rare. It is a good that you can win merely by getting enough base hits.

Obviously, the practitioner is obligated to check the few assumptions made in order to have confidence that a change in operating practice is indicated. The burden of proof always seems to fall on those challenging status quo. (However, another philosophy is that we now have evidence that the setpoint is not optimized, which puts the burden of proof on those who wrote the original specs to justify that position.) How far to move is also something that needs to be considered. Conservative moves may be a brief trial with a 10% move and evaluate the results carefully, especially if the response of interest is at the customer. Bolder

moves may mean halving/doubling the setting to get quicker answers. A couple of iterations should not only get you closer to an optimum, but also help construct the cost curves explicitly.

#### **EXAMPLE 4 – OPTIMUM NIP**

This next example will be much quicker to develop because we have laid all of the groundwork and explanations. This problem is to find the optimum layon roll nip for a specific case of film winding of laminates with low green tack adhesive. Here, the nip is ‘good’ because it excludes air which avoids the air buckle defect when air inevitably escapes from the sides of the roll during short term storage. This is especially severe with the laminates mentioned above because the plies will delaminate in a defect called tunnel wrinkles. We could, however, just as easily be trying to avoid more ordinary buckles as well as telescoping, flat tire rolls and a host of other loose winding defects. The principle is identical. In all cases, the nip will tend to reduce the loose winding defect and thus is good.

Rather than construct the poetic curves, however, we will analyze this problem in an even simpler fashion. We will merely ask the operator or process engineer why not turn the layon nip load up. The response is quite telling.

- 1) A confident “We can’t do that because \_\_\_ will get much worse.” Here, we will need to do optimization as discussed above.
- 2) An apologetic “We must follow specs.” Again, we will need to do optimization as above to see if the specs are serving us well.
- 3) A blank look, not sure or similar response. Here, we are confident that nip needs to be turned up because there is no obvious, known penalty. There certainly will be a penalty if we turned it up high enough, but we could be quite far from troubles when people aren’t sure what the penalty even is. Even if there were an unknown penalty close by, the move is still indicated. We must try a higher nip to see if relief might be obtained.
- 4) A confident “The nip knob is already pegged.” Barring the possibility of unknown additional nip capacity, we are pretty confident that the machine must be rebuilt to deliver higher nip loads.

The reason that I gave such a specific problem to work on is the surprising results from my field work. That is, in a half dozen of these nearly identical cases I’ve worked on, the nip needed to be turned up from where they were currently running. In all cases but one, the machine needed to be rebuilt to get there. In all cases but one, pegging the nip knob did not cause any noticeable issue. Even in this case, however, the penalty was merely crushed cores which can easily be stopped by thicker wall cores. This is analogous to moving the high nip cost curve down. The bottom line was that significant economic relief was literally at their fingertips had they used implicit optimization to clarify the situation. Figure 5 shows this situation as it currently stands in the industry for this specific problem.

#### **EXAMPLE 5 – OPTIMUM FLOW RATE**

This way of thinking is so powerful that you can attack some problems well outside your area of expertise. One such problem I worked on was in the textile industry. I got a call from the designer of a custom roll-to-roll textile ‘washing’ machine. The problem was that when the machine started up, the textile wrinkled almost continuously. The call came to me because one of my areas of expertise is in wrinkling. Even so, this expertise was neither needed nor used to quickly improve the process. I asked the engineer to describe his equipment over the phone. While the unwind and windup were conventional enough, I had trouble visualizing what was going on in the washing section. The best I could gather was that water was pumped down through a horizontal web run by nozzles on the top side and a collector on the bottom side. The wrinkles originated in the washing section, pretty clearly indicating this was the source of trouble. (Textile manufacturing and the unwind-to-washer sections could not possibly have had troubles of this severity leading me to believe that the web might be handled in conventional ways.)

I then asked the engineer what happened if you turned the water off. The reply was that “wrinkles went

away.” Next I asked why not reduce the flow rate. The reasoning is if full flow caused continuous wrinkles and no flow caused no wrinkles, then flow must be a bad thing. His response was “if we don’t wash the textile well enough, we will then have to rerun it until the dirt count falls below a specified maximum.” The last question is the telling one. I asked how often the material failed the dirt count spec and have to be rewashed. His answer was “so far we haven’t needed to rewash because the washer is so good.”

Thinking to myself that if the washer was really so good, why then was he calling me about wrinkles is not something I can share with the designer. Rather, I simply said that you must reduce the flow until the occasional rework is needed. 100% of all of the rolls were rejected due to too much flow (wrinkling) and 0% were wrinkled due to too little flow (rework needed). His setpoint was simply not sized or set properly to strike an optimum balance of the goodness and badness of water flow rate. Only after optimizing the flow knob and seeing where the total of wrinkle and rework costs fall out do we have any business adding new knobs such as by product or machine redesign.

The astounding thing about this problem is that we can determine an optimizing response from only a few key questions, without benefit of data or observation, on a one-of-a-kind process, not requiring expertise specific to the component or material, and to do this over the phone. Obviously, there is a benefit of being distant enough to avoid ‘not seeing the forest for the trees.’ Also, there is no emotional attachment to a design if you are not the designer. Granted, things like this can make it easier to offer constructive critique. However, the solution is readily available to anyone using an optimization mindset that assumes that there will be aspects of goodness and badness with every setpoint. Our task is to find the best balance for each setpoint or choice.

## **EXAMPLE 6 – OPTIMUM AMOUNT OF BEER TO HAVE THIS EVENING**

This way of thinking about the industrial world is so powerful, so adaptable and so easy because it does not demand a lot of data if you don’t have it or can’t justify getting it. However, this way of thinking can also be used outside of work. We will take a fun example just to illustrate the range of application of this method.

Our assignment is to find the optimum amount of beer to drink per day. Already this makes some assumptions. First, that you will drink beer. Second, that there is an optimum amount to drink. This is the same thing as saying that beer is both good and bad at the same time. However, we need not always select money as an optimum. Let’s try this. We will optimize using longevity as the objective function. By this I mean you want to find the amount of beer to drink that will, on the average, allow you to live the longest.

In order for this to make any sense we must do a couple of checks. Does beer consumption have bad effects on longevity? Obviously! The more a person drinks, the greater the risk of alcoholism, liver damage and accidents. And its not just car accidents. If you keep coming home drunk, you wife may shoot you. If this were all there were, the optimum amount to drink would be zero and the tea-totalers would be vindicated. However, whenever we get zero or infinity for an answer we must suspect that our information or model is incomplete. Now, we ask if beer consumption has good effects on longevity? The answer again is yes. Study after study indicate that the rate of heart attacks and some other health problems decrease with increasing alcohol consumption.

Now we are ready to plot the goodness and badness of beer as loss of longevity as seen in Figure 7. The optimum has been found by many medical studies to be 1-2 beers per day. (And no, you can’t save them up and binge on the weekend). This 1-2 beer optimum has qualifications. Specifically, it is for middle aged males drinking dark beer or red wine. Young males have greater penalties with regards to increased accidents and lifetime chance of developing alcoholism. Also, the benefit for women is much less, which moves the benefit curve down. The same is true for light beer or white wine which lacks the additional anti-oxidant benefits beyond pure alcohol. In other words, the more you know about the process, the better your answers will be.

The point here is not that beer is a good or bad thing in absolute terms. One could argue for a different

objective function, such as perhaps on moral grounds, which will give you a different optimum. It is simply that this way of thinking allows us new ways to think about and analyze process improvements. This ability to see the world as gray instead of black or white or black then white is enabling. For example, small amounts of many 'poisons' are medicines. (Digitalis and a key ingredient for rat poison are both used for heart patients.) Small amounts of allergens can make you healthier. (Children growing up on a farm or with pets have far less troubles with allergies). Small amounts of what used to be considered purely bad things, radioactivity, may increase lifespan.

## LIMITATIONS

All analysis has limitations. This particular analysis *may* apply to a specific analog problem, but will not be of much help in binary yes/no situations. Limitations may be found in the model itself because it inevitably generalizes and simplifies to make analysis tractable. Since there really is no model presented here, this analysis is not model limited. It is more a way of thinking than an equation or recipe. The only assumption made at the onset is that the objective is to maximize profit or minimize loss subject to whatever constraints are imposed. It would be hard to argue against the objective itself, because that is the *raison d'être* for business. One could, however, argue that any particular constraint may be inappropriate. For example, if a manager arbitrarily decides that something is not on the table for discussion, a less than optimum, optimum, may result. This is not that uncommon when dealing in emotionally charged situations, such as when dealing with customers. It is a very legitimate critique to note that constraints are not integrated into this analysis. With a wider field of view, one may optimize one's own short term profit but not be optimized for larger systems including suppliers or customers or optimized in the long run.

These concerns with modeling, however, are too complex and too removed from the plant floor to be much more than a distraction. Of more practical concern is the trustworthiness of the data that feeds the model. The explicit analysis requires trustworthy knowledge of costs that may not be at hand or readily obtained. The implicit analysis is far easier to apply, but it has other concerns. For example, it assumes that there is but a single optimum rather than two or more minima to the total cost curve. This is probably the case, but the technique would not show otherwise and would give less than perfect recommendations if there were more than one. Second, it assumes that the good and bad curves are smooth and not wildly different in shape. Third, it only allows us to optimize one thing at a time which may not produce a true optimum if there are interactions. True, there are multi-variate optimization programs that can tune systems, but they are far beyond the reach of any of us.

Just as with calculus, one must check not only where the slope of the cost curve is zero, one must also check the endpoints. It may be that the best setting is zero or pegged. If we do get pegged as an answer, then we are obligated to at least consider rebuilding the process to extend the range of that setting, especially if the slope is such that gains are still clearly seen by increasing the setting near its limit or conversely when the waste increases rapidly when decreasing from its limit.

A last area of concern is that there may be no practical optimum for some situations. For example, the secondary nip arm loading on a paper machine reel doesn't do much with regard to what is important. Almost all of the thousands of reels are set at 5-10 PLI even for widely varying grades from tissue to board. In almost all cases, you can set the nip at just about any point in that range and not see a difference in waste or delay. (One reason is that the control is so noisy due to mechanical friction that variation rather than setpoint dominates the results.) Another example would be web tension for heavy rubber or textile products. True, if the tension gets really low, the web may wander or wrinkle. True, if the tension gets really high (far beyond typical design capabilities), one could distort the material. But the 'window' is so wide that a Fred Flintstone control system is more than adequate. This cost curve is summarized in Figure 8a. Here, the cost curve is wide and shallow.

This leads us to the following generalizations. A setting may make a noticeable difference or it may not. If a setting *does not* make a big difference, the cost curve is flat through a sufficiently wide window and further effort is simply not justified. This case is shown in Figure 8a. If the setting *does* make a difference, then there will be an optimum either in the middle of the range or at the ends of the range. If the optimum is at the zero end, no further effort is justified as given in Figure 8c. This knob is bad news and should be

turned off for that situation. If the optimum is at the maximum or pegged end, as seen in Figure 8d, then you should consider a rebuild to increase range if the slope of the cost curve is significant there. However, the most common situation is where the optimum is in the middle of the range. There, optimization is indicated, especially if the total cost curve is sharp instead of shallow. This means that a knob is both good and bad at the same time. This is easy to recognize because the knob is, or at least should be, set at a midpoint (not pegged) and does make a difference.

## SUMMARY

A strictly engineering-based analysis will not yield a best solution for business. To strive for strength may make the bridge unaffordable or the airplane so heavy it can't get off the ground. A strictly statistical approach will also not yield a best solution for business. Increasing reliability such as by Zero Defects or Six Sigma, when taken to extreme, will yield extreme results; bankruptcy due to excessive costs. A best for business is to maximize profits or minimize losses. It may well be that the real best is something less than unbreakable or flawless. However, to find this business best at the plant floor level requires the integration of engineering, statistical and business models.

This way of thinking about the industrial world is so powerful, yet can be so easy to use because it does not make unnecessary demands on cost data. As we've seen with the examples using the implicit technique, process improvement may result from knowing as little as one or two readily obtained costs. If we have better cost information, all the better. We can get even better 'bests' using the explicit technique. It even allows us to progress from the implicit to the explicit approach when the simpler analysis moves us to a new position where we can get new cost information.

This way of thinking about the industrial world is also adaptable. We gave examples for optimum rejection, waste, tension, nip and flow rate. We could have just as easily optimized wound roll diameter or oven temperature. While most of the examples given were for web handling, that was merely to connect with common interests of this particular audience. The practitioner will see that it really has nothing to do with web handling, but all to do with better manufacturing practices.

This way of thinking helps us understand why we are sometimes stuck at certain levels of defects. This can happen when constraints, whether from customer, capitol, management or whatever, only allow us to adjust a few things. We may find, after open minded and careful study, that we are already near optimum on those allowed adjustments. The "fix it but don't change anything (much)" is clearly shown here to leave you tomorrow where you are today. It forces you to confront product and process redesign when allowable knobs are already near optimum. Redesign is needed when we need to move the cost curves when best is not good enough. This way of thinking keeps us from succumbing to too much of a good thing for extremist notions such as stronger is better, Zero Defects or even the current gospel of Six Sigma. If we are in business to make money, any analysis not built from the ground up on economics is simply incomplete. Finally, it extends our worldview from a binary black and white to an analogue gray.

Granted, most of our knobs are already near optimum, just don't make much difference or are constrained by something else. However, just because this or any other tool does not apply well in all or even most situations is not as limiting as might first appear. Newton's law is not useful in most applications because it doesn't offer much for chemical or electronics issues as an example. Similarly, Six Sigma is not useful in applications without sufficient data and not at all for small business or small business units. In fact, it has only recently been extended to medium sized business in a light version for Green Belts. Yet, no one would deny the utility of Newton's law or Six Sigma for the right problems.

Better questions may be how often can optimization be applied, how much does it cost and what are the results. I can only offer my own personal experiences as a consultant who does industrial problem solving for a living. I have found perhaps a quarter of the problems I work on can be solved or at least largely reduced merely by turning the right knob into a better position. In another quarter of the problems, the economic optimization viewpoint helped clarify the situation so constraints and tradeoffs are better understood. In almost all cases the cost is modest; perhaps a few hours of data mining and perhaps a short trial. This is because in my role I more often use the implicit version due to time constraints. People

working in the plants should be able to find even better results using the explicit formulation when it is appropriate for a given problem. The more costly the problem, the greater the justification for finding even better bests.

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Figure 1 – Projectile Path

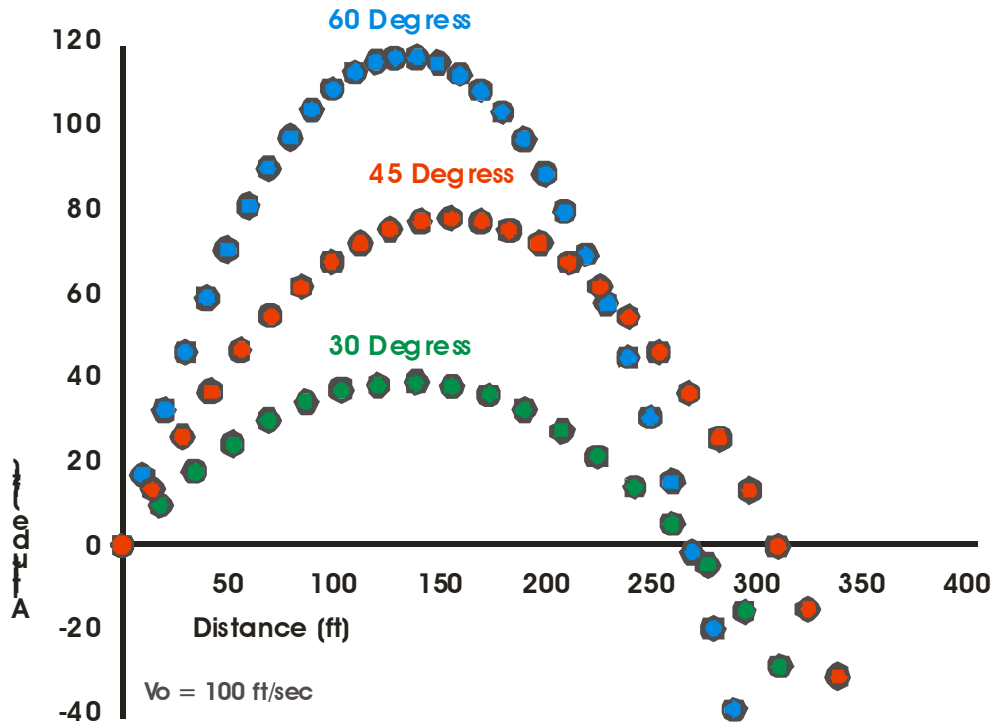


Figure 2 – Optimum Amount to Reject

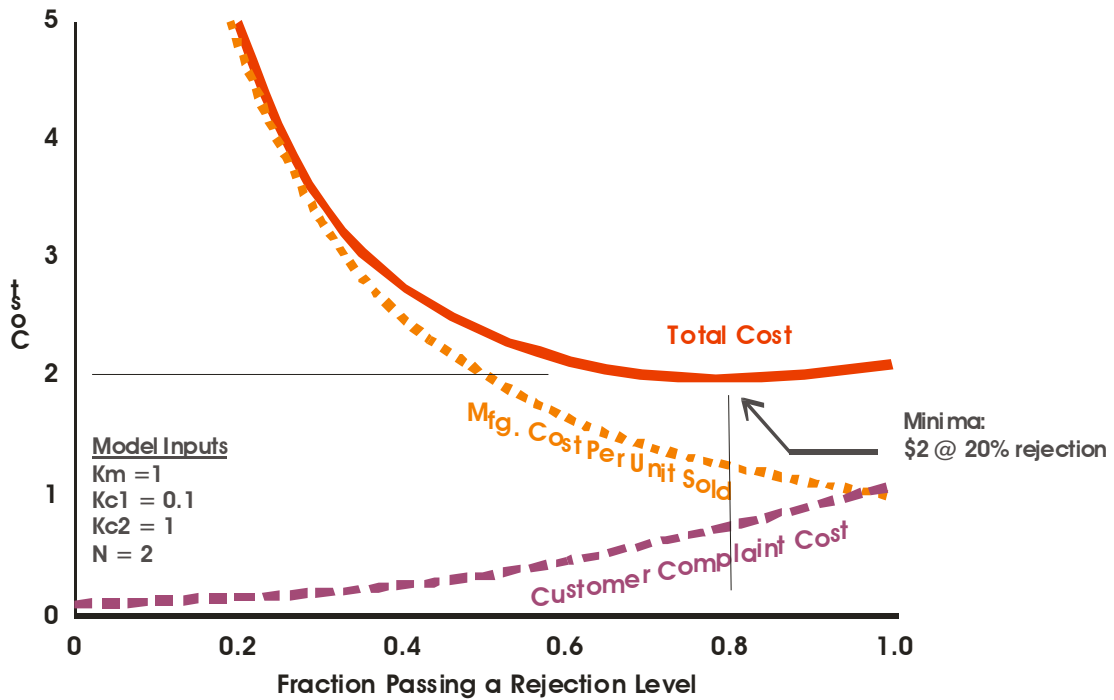


Figure 3 – Optimum Amount of Stub (Core) Waste

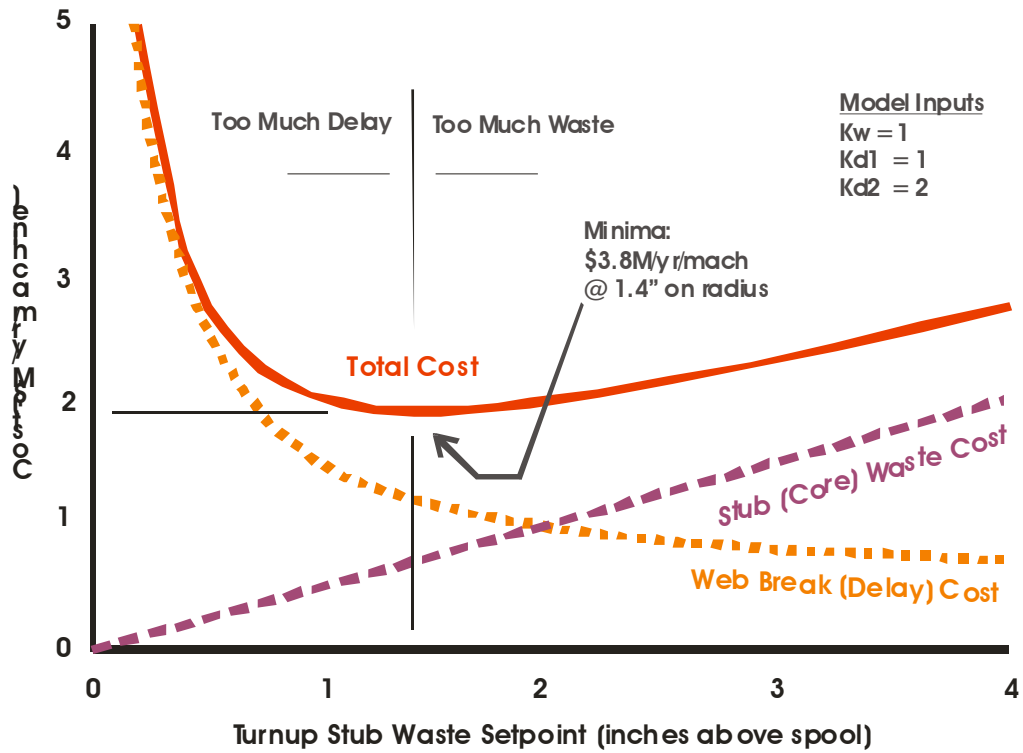


Figure 4 – Optimum Tension

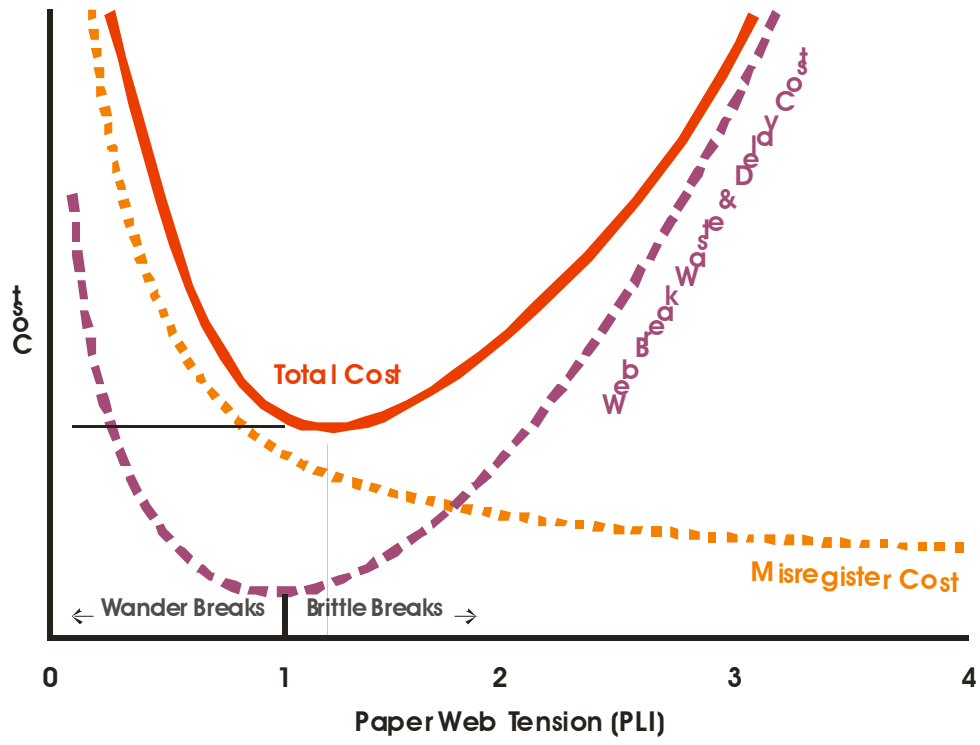


Figure 5 – Optimum Nip

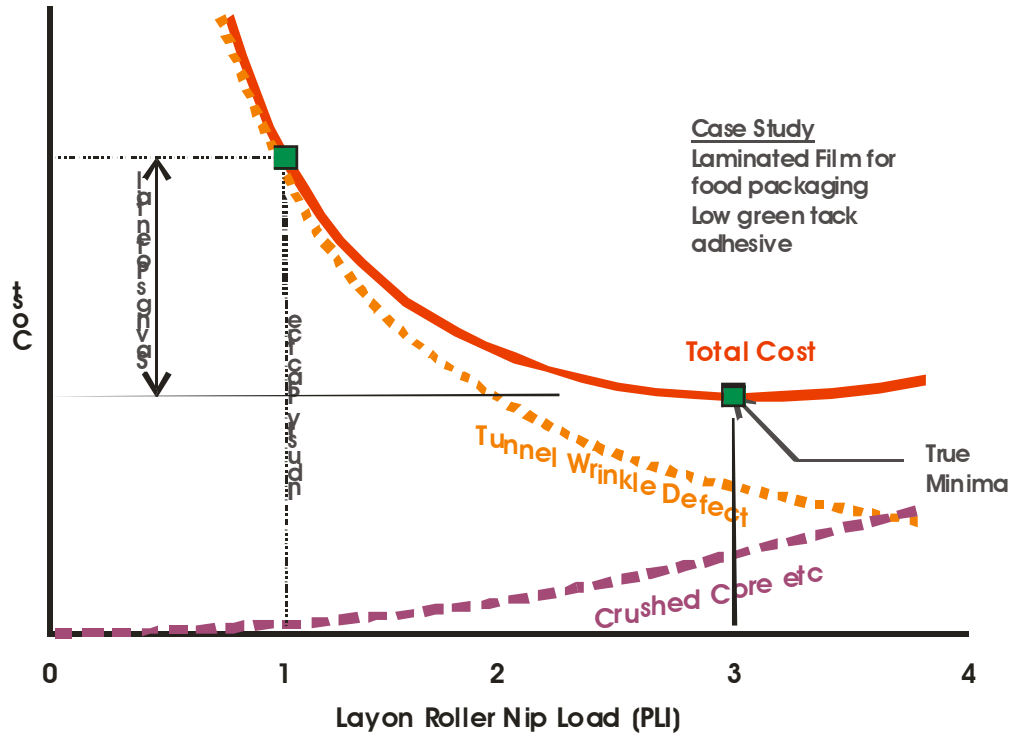


Figure 6 – Optimum Flow Rate

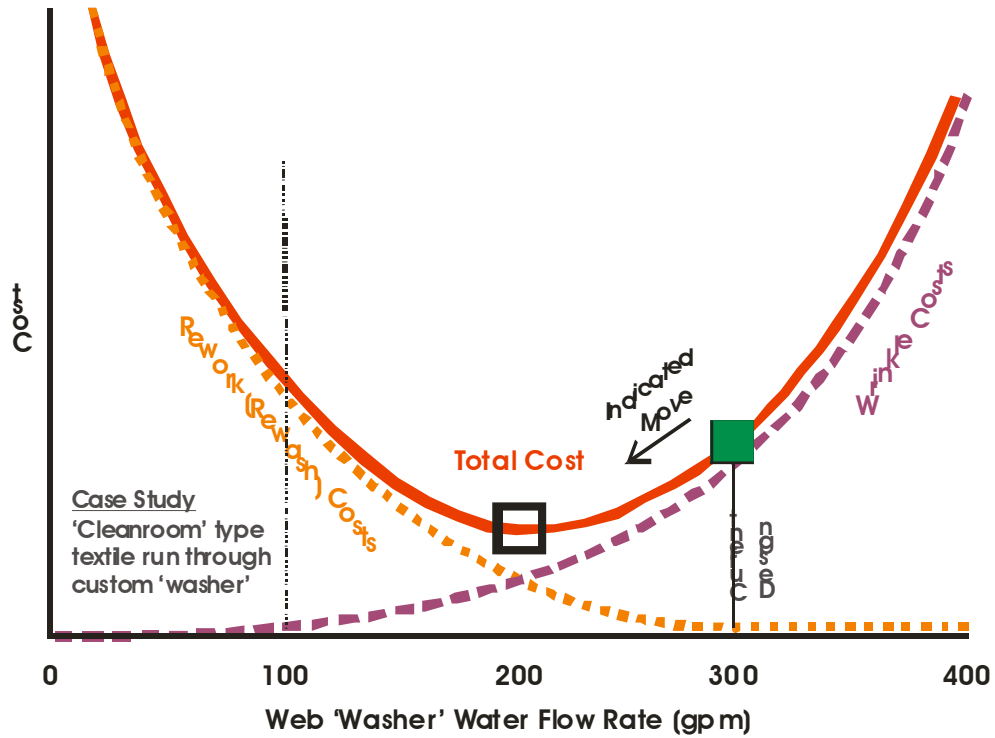


Figure 7 – Optimum Amount of Beer to Drink

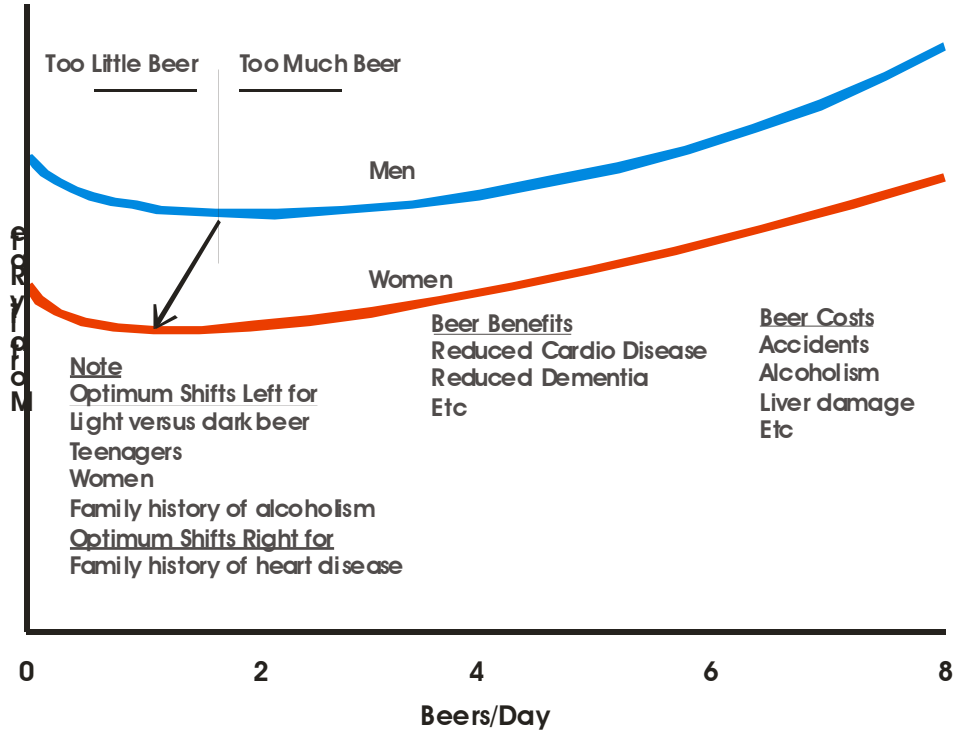
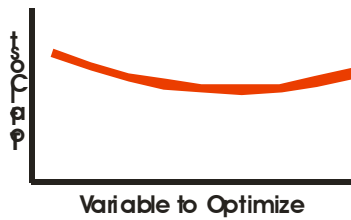


Figure 8 – Example Cost Curves



Case A  
Wide Window > Do nothing



Case B  
Narrow Window > Optimize



Case C  
Knob is Bad > Turn Off



Case D  
Knob is Good > Consider Upgrade