Why, When and How to Repair/Replace Key Process Rollers
(Or perform other routine maintenance affecting web quality.)

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ABSTRACT

High quality process rollers are critical to making high quality web products. Rollers may need to be replaced for one of three key reasons. The first is when the roller literally breaks. Little thought is needed in that case; the machine must be taken down immediately and a spare roller put in. The second case is under a preventative maintenance program that epitomizes best practices. The third case is much more common, but more poorly thought out. That is when the roller wears out. Here, surface problems such as degrading cylindricity means that the web quality becomes ever and ever more patchy or more streaky. Here we must decide when the roller must be replaced. This tends to be something of a grey scale. When is the situation too close to black to be tolerated? In most cases this is a qualitative call made when things become obvious to most. However, in this paper we will propose an entirely different and quantitative heuristic based on economics.

The underlying assumption here is that if you replace the roller too early, you cost your company more money in downtime and repairs. However, if you replace the roller too late, you also cost your company more money, this time it is in more waste, delay and customer complaints. There is only one time where roller replacement maximizes profit (minimizes loss). This paper shows how to get the costs of replacing a roller as a function of time in service. More importantly, this paper shows us how to get the costs of not replacing the roller as a function of time in service. By using simple calculus of minimas we can determine the economic optimum time to repair or replace a worn roller (Roisum, 2005).

The remainder of the article will outline some aspects of maintenance planning and the general process of roller replacement. Note also that the techniques taught here go far beyond roller replacement and might be applied to other maintenance items that can affect product quality.

WHY REPLACE ROLLERS?

Rollers maintenance, such as regrinding, resurfacing or replacing, might be performed for three general reasons.
1. Rollers did break (unplanned maintenance)
2. Rollers might break or get worn out (Preventative Maintenance)
3. Rollers wore out to the point of degrading web quality thus incurring real costs of waste, delay and customer complaint.

It is this third reason, wearing out, that we will focus on in this paper. Still, a few words about other failure modes might be in order for completeness. First of all, roller breakage is not very common. This is in part because a catastrophic roller failure can be a safety hazard and thus more conservative design and maintenance procedures are indicated. **Roller breakage**, when it occurs, may be one of the following modes.

1. Bearings fail early (before say a few decades) due to
   a. extreme conditions of heat or overload or contamination
   b. poor bearing selection
   c. poor bearing shielding/seals and lubrication selection
   d. poor design; such as not having an (axially) free bearing to allow for thermal expansion
   e. poor manufacturing such as excessive runout and imbalance (say greater than G2.5) that puts cyclic loading on top of the nominal loading
   f. poor installation such as fits and positioning
   g. poor maintenance
   h. poor lubrication (too much, too little, wrong type, contamination)
2. Journals fail at radiused steps due to a combination of bending (weight, tension, nip), torque (braked/driven rollers) and the stress riser at the radii. Usually this is a fatigue failure and will not occur right away or even soon.
3. Rubber covers fail catastrophically due to
   a. the cover chemistry not being suitable for the heat, loads or web machine chemistries
   b. the cover or sleeve debonds from the shell
   c. a chunk falls out, such as due to poor bond or due to an accident
   d. a cut or gash, also possibly due to an accident, but most commonly due to operators clearing a wrap with knives
4. Spalling of thermal and other thin metallic coatings from the shell due to reasons similar to rubber covers above.

In any case, a process roller or even idler roller that fails in such a fashion will usually do so with little notice and the failure will be somewhat sudden. An exception is that imminent journal fatigue may announce itself just prior as a noticeable increase in vibration. Of course, little notice does not mean no notice. Yet, some machines and maintenance are such that little notice is paid even when given because of a wide variety of economic and cultural reasons. In any case, the machine must be taken down, locked out and a spare put in place. This procedure could take anywhere from an hour to a day, though it could be a lot longer for some rollers buried deep within a machine and much longer still if a spare roller or other critical maintenance resource is not at hand. For the purposes of the discussion in this particular case, we do not choose when the broken roller will be serviced, the roller and its environment chooses when.
The second case of **preventative maintenance** of rollers is also somewhat uncommon. Yes, it is true that some paper mills have continuous monitoring of bearing condition (FFT of vibration signatures and other means). If so, premature failure (before a few decades) can sometimes be detected far enough in advance so that the bearing can be scheduled for maintenance on the next planned down, usually one of the major holidays. Also, some shell and cover conditions degrade slowly enough that replacement can be planned months in advance. This planned replacement could be made more gracefully than the failure resulting from the mill trying to eek out a few months even further on its life and the downtime then becomes unplanned.

**ROLLER WEAR**

Roller shells wear. Roller covers wear even faster. This wear tends to be streaky in nature, rather than patchy. Even if patchy, however, the patches often favor a lane making the wear somewhat streaky anyway. It is not entirely without coincidence that major quality troubles such as coating uniformity, bagginess and wound roll defects also tend to be streaky. Simplistically, the common shapes of wear might fall into one of the following categories as given in Figure 1 and listed below. Note that more complicated shapes can be built from the superposition of simpler shapes. For example, the combination of misalignment and excessive deflection would cause the roller to wear to a tipped convex shape. We could add a lane of contaminant to that for even more complexity. The troubleshooter will note that each of these three elements have totally different root cause mechanics even though the economic outcome, such as rejection of web, is similar.

1. Convex (frown shaped) such as in an excessively deflecting nip
2. Concave (smile shaped) such as due to an overcrowned nip, or tight or thick web edges.
3. Hourglass shaped due to wear caused by the edges cutting into the roller combined with changes in web width and/or position
4. Lane-like where there are wear bands (relatively low diameter) or contaminant build up (relatively high diameter)

What matters most of the time is only the part of the shape that contacts the web directly. Exceptions include very thin webs in a calender where fat, unworn ends can cause a reduction of nip on the web product itself. Roller wear is best measured as an ingoing roller grinding report that maps the 2 or 3D shape of rollers prior to regrinding (Huff, 2008). Non-contacting laser micrometers are capable of reading errors less than 2.5 micron (0.000,1 inch). Another technique, nip impressions can give similar clues (Genisot, 1994) (Swinak, 1997) and can be practiced for troubleshooting and/or PM. However, it is difficult to know whether the nip impression unevenness belongs to excessive combined deflection, side-to-side loading bias, wear on the top roller or wear on the bottom roller or the web itself being streaky or even a problem with the impression technique itself. This is not to suggest avoiding nip impressions and thus missing out on
the benefits of troubleshooting and PM that it might offer. Rather, it is only that this is not a direct measure of what you want: roller shape.

The rate of roller wear depends mostly on combination of the abrasiveness of the web and the abrasion resistance of the cover or shell. Paper is more abrasive than film, though fillers, such as clay, and opacity agents, such as TiO, and coatings can increase the abrasion far beyond the base web that is wood fibers. Fiberglass is another notoriously abrasive web. Similarly, there is a great difference in abrasion resistance of metals. In general, the harder the metal, such as measured by Shore or Rockwell instruments, the better the abrasion resistance. Metal hardness is a much easier measurement to make than abrasion resistance though the latter should be considered for serious work (Stavros, 1998). Harder covers are much more durable than softer covers and thus not surprisingly 90 Durometer polyurethane wears better than 80 Durometer polyurethane that wears much much better than silicone for example. Dual Durometer covers can help with some ‘have your cake (cover softness) and eat it to (cover durability)’ challenges.

Despite all of these variables, however, the average rate of roller wear is probably approximately steady with time though it is almost certain to be streaky across the width, i.e., profiled. Average roller wear could be measured as a volume (mm^3/week) or diameter (micron/week). While the average rate of roller wear may well be reasonably steady with time (though streaky and lane-like across the width), the effects are not. Wear levels far below the ‘threshold of pain’ do not cause a proportional response as a function of time. However, as you approach the threshold of pain you begin to get an exponential increasing rate of economic issues such as (internally rejected) waste, delay and customer complaint. Some grades and some customers will see troubles first, but all will see troubles as the condition of the roller (or key process element) is allowed to degrade even further. We will have more to say about measuring and modeling this ever-increasing costs of waste (delay and customer complaint) shortly.

THE COSTS OF REPAIRING/REPLACING A ROLLER

The costs of repairing or replacing a roller are relatively easy to obtain. In anticipation of the next sections, these costs will be expressed as $/week (or Euros if you like as the denomination is unimportant). What we need to know is the cost of the roller, the costs of regrinding, the number of regrinds before the roller must be totally replaced and, finally, the cost of downtime.

1) \[ c_{\text{repair}} = c_{\text{down}} + c_{\text{regrind}} + \frac{c_{\text{replace}}}{N} = \frac{A}{t} \]

where

- \( c_{\text{repair}} \) = total cost to repair ($/wk)
- \( c_{\text{downtime}} \) = costs of downtime such as crew, lost profits etc ($ per repair)
- \( c_{\text{regrind}} \) = costs of regrinding such as shop rates for the grinder, storage, etc ($ per regrind)
\[ C_{\text{replace}} = \text{costs of replacing the roller} \quad (\$ \text{ per roller}) \]
\[ N = \text{number of regrinds before a roller needs major refurbish or replacement} \]
\[ A = \text{total cost to repair per event} \quad (\$) \]
\[ t = \text{time in service} \quad (\text{weeks}) \]

Note that if a roller can’t ever be reground and must always be refurbished or replaced, \( C_{\text{regrind}} \) is 0 and \( N = 1 \).

So, let us take an example that is very approximately what a paper mill calender roller might have. This is by no means restrictive because the principle holds whether your roller costs $10,000 or $100,000 or whether downtime costs $100 per hour (tiny converting machine) or $10,000 per hour (paper mill, foil mill etc) or whether the roller is a calendar, coater or printer. Indeed, the analysis also applies equally well to other key process elements such as slice lips (paper) or extrusion dies (film) and much much more. Here will will use nice even numbers to make things simple so that the principles rather than details stand out.

Example 1 – Paper Machine Super Calender Roller

\[ C_{\text{downtime}} = \$10,000 \text{ per hour for a one hour downtime} \]
\[ C_{\text{regrind}} = \$10,000 \text{ per regrind} \]
\[ C_{\text{replace}} = \$100,000 \text{ per roller recover and refurbish} \]
\[ N = 10 \text{ regrinds before the roller needs a major refurbish} \]
\[ t = \text{time in service} \quad (\text{weeks}) \]

It is easy to see now that the total costs are $30,000 per roller repair event and that costs as a function of time in service are \( 1/N \). The plot of these costs are given in Figure 2. Thus if the service interval time is 3 weeks, the costs of repairing are $10,000 per week and if the service time interval is 30 weeks, a bit on the long side for this application, the costs would be only $1,000 per week. With an oversimplified view of economics such as only considering repair costs, you would have to conclude that the optimum (minimum cost) time in service would be ‘until the roller broke.’ This unfortunately all too common approach, as we will see shortly, is not at all optimum for almost any situation. The reason is, that we are not consider the costs of NOT repairing.

**THE COSTS OF NOT REPAIRING/REPLACING A ROLLER**

The costs of not repairing/replacing a roller are a little bit harder to get, but all the more important to do so. We make the quite reasonable assumption that roller wear matters to web quality. This is not hard to demonstrate in the extreme. What we need to do is to consider the costs when they are *not* so extreme, but nonetheless, quite real. So, what would the performance of a machine, or in this case machine part, look like as it aged. The long studied standard analysis of this type is generally known as the Weibull distribution. It is used for reliability studies and prediction in uncountable applications. As seen in Figure 3, the Weibull curve has three regions: infant mortality, normal life and wear-out. Infant mortality is caused by defect parts, materials or installation. While
notable for some machines, such as electronics, we will not consider infant mortality here. The first reason is because infant mortality adds complexity and the second is because infant mortality is not as big of a concern as wear-out which is the subject of this paper. Note, however, that the techniques taught here would allow someone to consider this early life failure if they wished to go through the bother.

Another simplification is that while we must acknowledge that the failure rate of parts might approximately follow the bathtub curve in most cases, we will not use the PDF (probability density function) math models that are commonly used to fit the curve. Instead, we will first attempt to grow our own by fitting the failure rate as a much simpler polynomial in the form of costs in $/week. Part wear-out, such as a key process roller, will cause ever increasing costs of waste, delay and customer complaint as seen in Figure 4. The costs of NOT repairing will be then be expressed as

\[ c_{\text{NOT repair}} = D + Et + Ft^2 \]

To obtain these (not repair) cost coefficients we merely need to fit a curve of the total costs of waste, delay and customer complaint as a function of time in service. To simplify, because all of these individual cost are likely in different ‘databases,’ we can simply use internal waste as a proxy knowing that it is conservative in the sense that delay and customer complaint will also increase as a part wears out.

Once this fitting has been done we have the economic minima problem that I first introduced a decade ago (Roism, 2005). The analysis is summarized in Figure 5. The costs of repair is a 1/t problem where costs go to infinity as one repairs ever sooner such as a day, an hour or a minute and then approaches zero as the part is almost never changed. If this were the only consideration the best solution would seem to leave the part in forever.

However, we know that never changing a key part can not possibly be optimum. Indeed, the cost of NOT repair begins at some base line level that is the D coefficient in our fit. This is the other causes not associated with wearout of the part under consideration such as having a problem that has more than one possible cause. Let us take a specific case of corrugations in paper mills. Here we know that calender wear is but one of the bigger causes. Slice lip problems, wire and fabric plugging are probably similarly strong. Note, however, that this analysis applies to any forming element. So, for example, we know that die lip wear on a blown film extruder is a major cause of gage variation that in turn causes bagginess when the web is wound. Still, we know that extruder temperature profiles, air currents touching the bubble and the primary nip also can make bagginess. If we were studying the die lip service frequency the D would be those factors plus the quite likely possibility that even a brand new die is still not uniform or precise enough to cause no bagginess whatsoever.

Returning to the graph we note that the sum of these two curves has a minima. The location of that minima is what we seek, specifically the optimum service frequency interval that minimizes the total costs of repair and NOT repair. If we use the calculus of
minimas, we note that this will occur when the slopes of the curves are equal in magnitude, but opposite in sign. (Not where they intersect as some might believe). This slopes are the derivatives thus

3a) \[ -\frac{dc_{\text{repair}}}{dt} = \frac{A}{t^2} \]

3b) \[ -\frac{dc_{\text{NOT repair}}}{dt} = E + 2Ft \]

Setting 3a and 3b equal and bringing bringing everything to one side we see the classic cubic equation, albeit missing the second term.

4) \[ -A + 0Dt + Et^2 + 2Ft^3 = 0 \]

We can make a couple of important observations here. The first is that the D coefficient does not matter. What this means is that the optimum service interval for a part does not really depend on other factors (each of which has its own optimum). Obviously this breaks down a bit if you consider the desirability of repairing more than one critical quality item (that affects waste, delay and customer complaint costs) during a single down, but we will just leave it simple for the moment. The second issue is more important. That is to note that a cubic equation has three roots, but only one will be ‘real’ for this case. You can look up on the internet the solution if you wish. However, we will take a different approach for two reasons. The first is that the equation is complicated and thus the solution may not be convincing to some. That the equation will produce at least one square root of -1 problem does not add to confidence. The second is that the graphical method suggested next is equally valid, easy to do and easy to understand.

DEALING WITH NOISE IN THE NOT REPAIR COST CURVE

The world is complicated and thus may not conform to simple expectations. These will result in ‘noise’ in the waste signal. How do we extract the waste signal from this noise? Two techniques will be used here. The first is to average several service cycles together. So, for example, if a normal service interval is 6 months, we should try to get economic data going back at least 4 cycles, in other words 2 years for this example. Fortunately, almost all plants have internal waste data going back at least that far so this should not be limiting. What may be more limiting is that economics will be less noisy if that period did not include any major rebuilds of machine or mix of ‘grades’ or changes in reject criteria.

What we are looking for is a sawtooth pattern in the waste data as seen in Figure 6. Here we see four service intervals that begin with a new (or reground) roller and end when that roller is serviced by changing it out with another new (or reground roller). During each interval the waste increases, though very noisily as we see here. So our first step is to ‘slice’ the data from 4 periods and stack them on top of each other.
The next step is to do a regression on the data. In this case we will use a polynomial of degree 2. This should not only cover most situations well enough, but it is also simple enough to be analyzed either using the calculus of minimas as given above or graphically as we do here because it is much simpler. As seen in Figure 7, the fit is quite good for this example. If the fit is not good in your particular case, we have several things that can be done to improve it. The first is obvious, more data. That is we include more time and service cycles. There is no reason per se that one might not include data from other machines and other plants, provided that they are similar enough. Even so, more data does not always improve the picture. For example, if we change our grade mix or change our customer mix or change our reject criteria; we might expect even more noise. Filtering to only include a fussy grade or fussy customer or a better defined defect rejection might reduce noise.

**FINDING THE ECONOMIC OPTIMUM SERVICE INTERVAL**

We have two methods to find the optimum service interval. The first is to use the calculus of minimas to find the optimum. The coefficient A was obtained in equation 1 and the coefficients D (that does not affect the calculation) E and F are given in the fit such as given in Figure 7. Then the roots of the cubic equation can be found by going online to get the equations or using an online service such as MatLab or Wolfram Alpha. If we are fortunate enough to find that a linear equation fits the NOT repair costs well enough, we have a much simpler quadratic equation to deal with that the reader can recall from high-school maths.

The second method requires no maths whatsoever. Here we will use a graphical technique to find the optimum service interval. As seen in Figure 8, we merely add the costs to repair and the costs to not repair together. The minima seems to clearly lie somewhere between 7 and 21 weeks, so averaging we get 14 weeks that is remarkably close to the value you would obtain from calculus.

**COST SAVINGS AND OTHER OPPORTUNITIES**

The first question anyone should have at this time is so what? How much are we really going to save by going through this analysis? In our example it would take 30 weeks for defects to double their minimum rate and be clearly noticed. If so, the costs and cost savings works out like this.

- $11,100/week at 30 weeks
- $8,400/week at optimum of 14 weeks
- $2,700/week savings using optimum instead of obvious

$140,000/year for a single key element!
If you take the trouble to fit the NOT repair costs and the fit is decent, you may have yet another opportunity. That is to see if the data might be mined for other elements that might need more frequent servicing. However, as seen in Figure 9 for our data (only 1 service cycle), the difference between actual waste costs and fitted waste curve appears to be pure noise. Further opportunities offered by residuals seem to elude our analysis here. That is not to say that secondary or tertiary elements might not be found using techniques similar to outlined here. Your next analysis might show a connection or perhaps you use more powerful statistical techniques to glean the trends that might elude those less capable such as I.

SPARE PARTS AND TIME TO REGRIND

One mill I worked with had just such a corrugation issue that was largely determined by the current cylindricity of a single calendar element. Their normal regrind interval was 4 months, clearly too long for the economics, so I suggested 3 months. However, to do so meant that they would have to buy a 3rd roller. One would be in service, the second in spares and the third in the shop or enroute. (The ability to deal with an unplanned accident always requires an additional roller to be kept in spares). The reason was that it took several months to move a roller to a shop, get it reground and return it to spares. Unless one wanted to pay the shop upcharge of a fast turnaround, another roller would be needed. However, as we’ve seen in the previous material, the costs of roller purchase is already included in the economics.

Another note is that this analysis does not preclude unplanned downs. Yes, if the roller is damaged in an accident the machine must go down for repairs. However, the next repair might be scheduled as given above if accidents were avoided during that period. Similarly, PM is also not precluded. You may change parts out pre-emptively before the product is damaged in any economic way. A perfect example here is slitter blades, especially razors. If you must change one blade you might as well change all. Similarly, you may change parts out pre-emptively because you are already down for some reason or on a major rebuild. Still, none of that detracts from the utility of the far more common case of normal service intervals where wear-out begins to degrade product quality.

HOW TO CHANGE A ROLL OUT SAFELY

Lock-out-tag-out
Take Two … for Safety\textsuperscript{TM}, by DuPont\textsuperscript{TM}
(Think about what you are doing before you do it)
Follow safe procedures spelled out by machine builder or machine owner
Keep non-maintenance personal away during the service
HOW TO CHANGE A ROLL OUT EFFICIENTLY

Roll change and many other routine activities lend themselves to a really fine industrial engineering program called SMED (Single Machine Exchange of Dies). You could read a book or go to school to fill in many details and learn the techniques that are summarized by four basic principles.

1. Prepare for the down BEFORE by:
   a. Having a maintenance plan (something like a Gantt chart)
   b. Having people and parts and plan ready at the machine before it goes down
2. Eliminate all unnecessary activities during down
3. Parallelize activities to the extent possible/reasonable
4. Speed up the critical path by studying it and supplying tools and techniques

An everyday example here is a pit crew in a car race can change all four tires in less than 15 seconds while any of us would take at least 15 minutes to do just one tire on our own car. An exaggerated example of step 3 above for an electric motor change would be simultaneously:

1. A millwright removes the mounting bolts
2. Another millwright detaches the cooling and fan ducts
3. A rigger attaches the chain hoist
4. An electrician detaches the power and instrumentation cables

The above examples are slightly exaggerated by either assuming resources that we might not have or by resources that could get in the way of each other. Still, there is great merit in making routine downs as efficient at possible by noting the (down and maintenance) repair costs are always in the thousands of dollars per hour.

GRINDING, STORAGE AND RIGGING

Grinding rollers is a topic well beyond this paper. Suffice it to say, however, that the quality (and thus price) varies enormously between shops. Most plants do not have their own grinding facilities and thus contract everything out. Most paper mills, on the other hand, do have a grinding shop that in some cases may rival some of the best builders and suppliers. Grinding cylindricity tolerances and precisions also varies considerably with material. It is possible to get metal about 10X closer than you can rubber covers, say at its very best around 2 microns for metal and 20 for rubber. Very best in theory would be ground in situ, but it is seldom possible to get high quality grinding that way. Second best is to grind in bearings at a very stabilized temperature that may take days to reach for very large rollers. Grinding on journals is sometimes easier, but does not always result in the best precisions.

Rollers are supported in storage either on their journals or on their bearings. Precision rollers are often stored at room temperature and occasionally very large ones are slowly
rotated to keep them from taking a mechanical or thermal set. This allows the spare to be ready at a moment’s notice. Roller surfaces may be protected from casual bumps by tarpaulins or corrugated cardboard. They may also be poly wrapped to keep out moisture or contamination. When transported via truck or rail, rollers may be further protected by wooden crates. Rigging is the process of using cranes and hoists and other devices to move a roller into or out of a machine. Rollers are usually supported via their journals using soft strapping that is rated and inspected to be safe for the load.

SUMMARY OBSERVATIONS AND APPLICATIONS

This analysis shows how most rollers are changed out on intervals defined by obvious breakage or wear-out. The opportunity is to use economics to define the optimum service interval that minimizes the total costs of repair and NOT repair. This paper showed how to extract the NOT repair cost curve most simply from waste data that every plant has. As noted, however, that internal waste is not the only cost of NOT repair. You can also expect increases in customer complaints as no quality system is perfect in culling. If you include the costs of complaint the true optimum service interval would be more frequent than we found here using only the convenient internal waste. If you include the costs (risks) of losing a customer, the optimum service intervals are even shorter still. Thus, our example of saving $150,000 per year for just one key paper machine element probably underestimates the true savings.

Our example was, necessarily, a single case history of a key process element in paper making. There is no reason not to use similar analyses for other key elements in paper such as slice lips, wires, forming fabrics and press rollers. There is no reason not to use similar analysis for film for key elements such as die cleaning and die lip refurbishing. There is no reason not to use this analysis on printing rollers, printing blankets, slitter blades or any other converting element that routinely causes quality issues.

BIBLIOGRAPHY

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**FIGURE 1 – SIMPLE ROLLER WEAR SHAPES**

- **Taper**
- **Smile**
- **Frown**
- **Ridge**
- **Valley**
- **Step**

**FIGURE 2 – COSTS TO REPAIR**

The costs to repair can be expressed as:

\[
C_{\text{repair}} = \frac{C_{\text{down}} + C_{\text{regrind}} + \frac{C_{\text{replace}}}{N}}{t} = \frac{A}{t}
\]

Where:
- \(C_{\text{down}}\) is the downtime cost.
- \(C_{\text{regrind}}\) is the regrind cost.
- \(C_{\text{replace}}\) is the replace cost.
- \(N\) is the number of replacements.
- \(t\) is the time in weeks.
- \(A\) is the total cost over time.
FIGURE 3 – THE WEIBULL DISTRIBUTION

FIGURE 4 – THE COSTS TO NOT REPAIR
FIGURE 5 – FINDING THE ECONOMIC OPTIMUM SERVICE INTERVAL

FIGURE 6 – THE SAWTOOTH WASTE CURVES
FIGURE 7 – REGRESSION OF THE NOT REPAIR COST CURVE

\[ C = 5.153030808 \cdot 10^{-3} x^2 + 2.902808091 \cdot 10^{-2} x + 5.154889796 \]
\[ R = 0.87 \]

FIGURE 8 – A GRAPHICAL METHOD TO FIND THE OPTIMUM SERVICE INTERVAL
FIGURE 9 – SEARCHING RESIDUALS FOR OTHER OPPORTUNITIES

Time (weeks)