Paper Quality Simulation

by Pat Dixon

The objective is to simulate the resulting paper quality in a dataset of process variables and measurements such as PulpEye and lab test results. These calculations are not intended to perfectly match actual paper machines, but to give reasonable steady state responses with process dynamics so that a dataset can be generated for testing modeling and control applications.

Most of the steady state relationships are exponential curves where the asymptote represents the value which cannot be physically exceeded.

This is an internal Pulmac document. This design will be used to produce the dataset that will be distributed to outside vendors. We want the vendors to find the relationships in the data without knowing the origins of those relationships in this design.

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1. Process Measurements

Process measurements consist of sensor values in a control system (designated as MV for Manipulated Variable). An MV is a high frequency sample rate, typically 1 sec to 5 sec. The dataset has MVs that are mostly independent variables, but in some cases an MV may be a state variable that is calculated from other MVs.

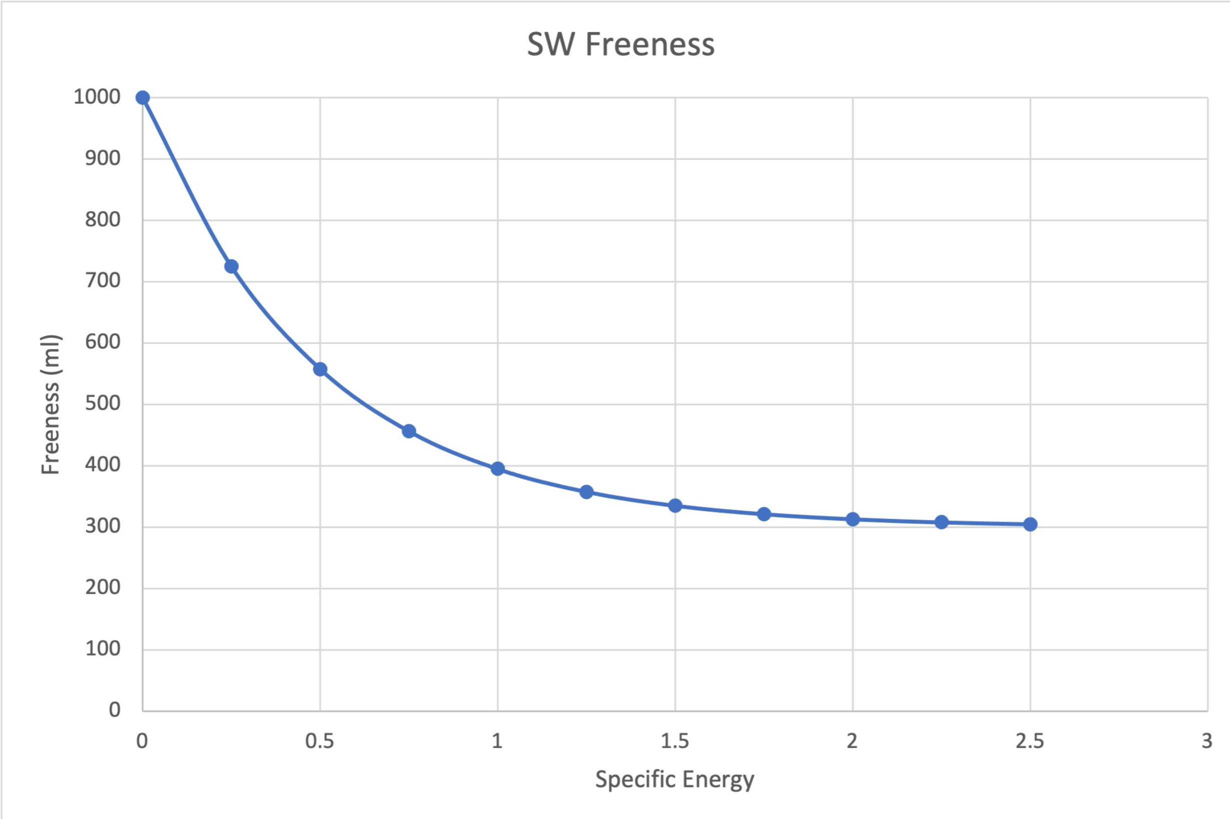
1.1. Furnish Percent

There are MVs for the flow rate of softwood, hardwood, and recycle. Additional state variables are added to the dataset which are simply calculated percentages of each furnish.

1.2. Furnish Freeness

The assumption is that freeness will be a function of refiner specific energy as follows:

$$Freeness = 1000 - 700 * \left(1 - \frac{1}{e^{2*SpecificEnergy}}\right)$$



The dynamics are immediate. The process measurement would ideally be from a Conmark VCT sensor at 1 second sample rate.

1.3. Jet to Wire Ratio and related calculations

This really is not a quality measurement, it is a control loop. However, there are process variables that depend on this ratio and we will assume this is a control loop that automatically adjusts and affects other process variables.

We will start with stock flow to the headbox and slice opening to calculate a headbox pressure. It is recognized that Thin Stock Flow to the headbox typically has recirculation, but for simplicity we will ignore this as assume all Thin Stock Flow goes to through the slice. The velocity can be calculated from mass flow:

$$JetVelocity\left(\frac{Ft}{min}\right) = \frac{\dfrac{StockFlow\left(\dfrac{Gal}{min}\right)}{7.48\dfrac{Gal}{Ft^\wedge 3}}}{Trim(Ft) * \dfrac{Slice(in)}{12\dfrac{in}{Ft}}}$$

Dynamic response of JetVelocity to Thin Stock Flow is immediate

Dynamic response of JetVelocity to Slice is immediate

The jet to wire ratio is simply:

$$JetToWire = \frac{JetVelocity}{WireSpeed}$$

We can use the Bernoulli relationship to determine headbox pressure:

$$JetVelocity^2 = 2g * HeadboxPressure(Ft)$$

$$g = 32.2\frac{lb_m * Ft}{lb_f * second\text{^}2} = 32.2\frac{lb_m * Ft}{lb_f * \left(\frac{second}{60\frac{second}{min}}\right)\text{^}2} = 115{,}920\frac{lb_m * Ft}{lb_f * min\text{^}2}$$

$$HeaboxPressure(Ft) = \frac{JetVelocity\left(\frac{Ft}{min}\right)\text{^}2}{2 * 115{,}920\frac{lb_m * Ft}{lb_f * min\text{^}2}}$$

1.4. Machine Speed

This will simply be a draw multiplication with immediate dynamics

$$MachineSpeed\frac{Ft}{min} = WireSpeed\frac{Ft}{min} * (1 + DrawRatio)$$

2. PulpEye Measurements

PulpEye measurements are process inputs in the same way as MVs, but at a much slower sample rate such as 5 min.

2.1. Blend Chest Freeness

For a PulpEye sample of freeness after the blend chest, we will simply use the fraction of each flow to the blend chest to calculate a weighted average. We will assume we have 3 furnishes:

1. Softwood
2. Hardwood
3. Recycled

Therefore, we will use the percentage of each of these flows and their freeness values to calculate the weighted average:

$$StockFlow\left(\frac{Gal}{min}\right) = SoftwoodFlow + HardwoodFlow + RecycledFlow$$

$$BlendFreeness = SoftwoodFreeness * \frac{SoftwoodFlow}{Stockflow} + HardwoodFreeness * \frac{HardoodFlow}{Stockflow} + RecycledFreeness * \frac{RecycledFlow}{Stockflow} +$$

Dynamic response of BlendFreeness to any of the furnish freeness values:

- Deadtime: 5 minutes
- Time Constant 1: 2 minutes
- Time Constant 2: 1 minutes

2.2. Blend Chest Crill

There are dataset independent variables for crill of each furnish. While refining specific energy might effect crill, we do not know the incoming crill before it is refined, therefore crill for each furnish is an independent variable. This PulpEye state variable is simply a weighted average of crill in the blend chest. It is calculated in the same manner as freeness above.

3. QCS Measurements

CQS measurements are primarily state variables that are calculated from the prior inputs. A typical scan rate is 1 min. The values are meant to present a scan average.

3.1. Moisture

Moisture will be calculated in 3 steps:

- Drainage on the wire as a function of freeness
- Drainage on the press as a function of nip pressure
- Final moisture on the reel as a function of dryer steam pressure

3.1.1. Wire Drainage

According to a thesis by Reardon in 1994, some numbers to go by are:

- “to the headbox at a consistency of around 0.8-1.0% solids.”
- “As the paper sheet leaves the couch roll the solids content represents around 20% of the total sheet weight.”

Using a basis of 100 lb stock, the headbox consistency of 1% would have 99 lb water, 1 lb fiber
With 20% leaving the wire, there would be 1 lb fiber in 5 lb stock, with 4 lb water
That means 95 lb water drained out of 99 lb, so 95% of water drained on the wire

$$FiberToHeadbox\left(\frac{lb}{min}\right)$$
$$= StockFlow\left(\frac{Gal}{\mathrm{min}}\right) * \frac{Consistency\left(\frac{lb_{fiber}}{lb_{flow}} * 100\%\right)}{100\%} * 8.3\left(\frac{lb_{flow}}{Gal}\right)$$
$$WaterToHeadbox\left(\frac{lb}{min}\right) = StockFlow\left(\frac{Gal}{\mathrm{min}}\right) * 8.3\left(\frac{lb}{Gal}\right) - FiberToHeabox\left(\frac{lb}{min}\right)$$

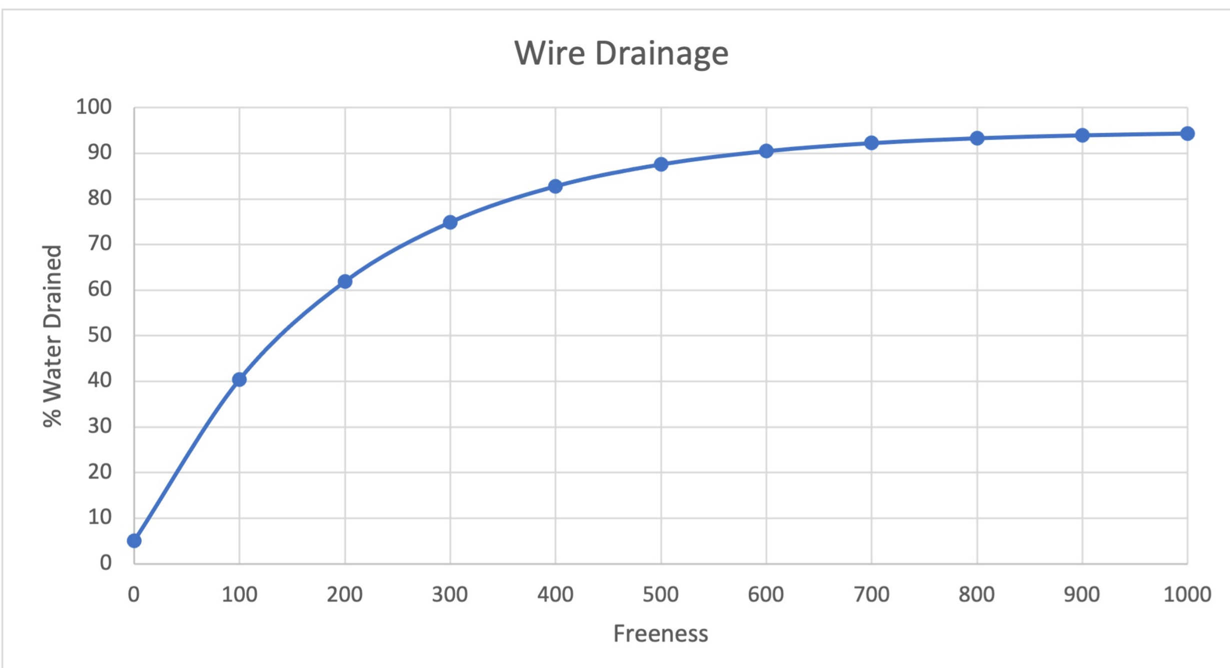
The drainage on the wire is dependent on several process variables:

- Wire speed: The effect goes both ways. Faster speed can increase vacuum force from foils but the dwell time on the wire is less
- Freeness: The higher freeness gives more drainage

Therefore, we will only use freeness as a variable

We will assume with a freeness of 0 ml, we will get 5% drainage on wire. Therefore, starting at 5%, as freeness goes up we will not exceed 95% of water drained.

$$WireDrainage\% = 5 + 90 * \left(1 - \frac{1}{e^{\frac{Freeness}{200}}}\right)$$
$$= 95 - \frac{90}{e^{\frac{Freeness}{200}}}$$



Dynamic response of Moisture at reel to Freeness:

- Deadtime: 20 minutes

- Time Constant 1: 5 minutes
- Time Constant 2: 5 minutes

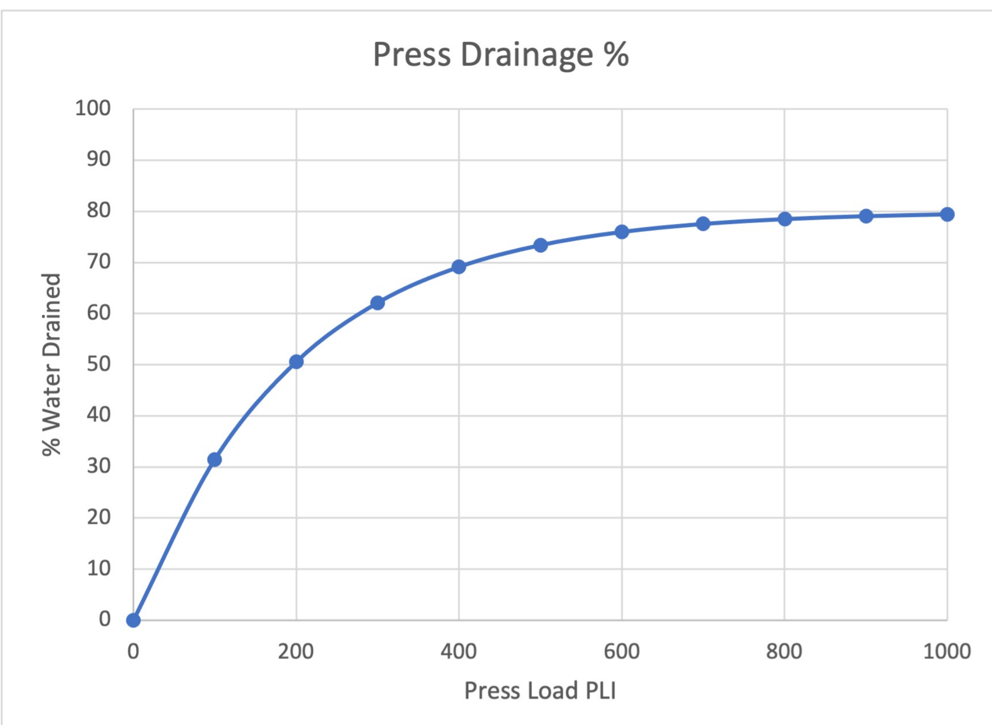
3.1.2. Press Drainage

$$WaterToPress\left(\frac{lb}{min}\right) = WaterToHeadbox\left(\frac{lb}{min}\right) * WireDrainage\%$$

From Reardon: “The final wet basis moisture content is usually around 60%, or 40% solids.”

With a basis of 100 lb sheet at 20% solids coming off the wire, there are 20 lb fiber and 80 lb water
If we assume an average of 50% solids out of press, there are 20 lb fiber and 20 lb water
That means 60 lb water removed out of 80 lb, which is 75%
We will assume the press removes no more than 80% of water in the sheet from the wire

$$PressDrainage\% = 80 * \left(1 - \frac{1}{e^{\frac{PressLoad}{200}}}\right)$$



Dynamic response of Moisture at reel to PressLoad:

- Deadtime: 1 minutes

- Time Constant 1: 0.25 minutes
- Time Constant 2: 0 minutes

3.1.3. Dryer Drainage

At this point we will switch from a mass balance to a curve which limits the final moisture. We begin by completing the mass balance:

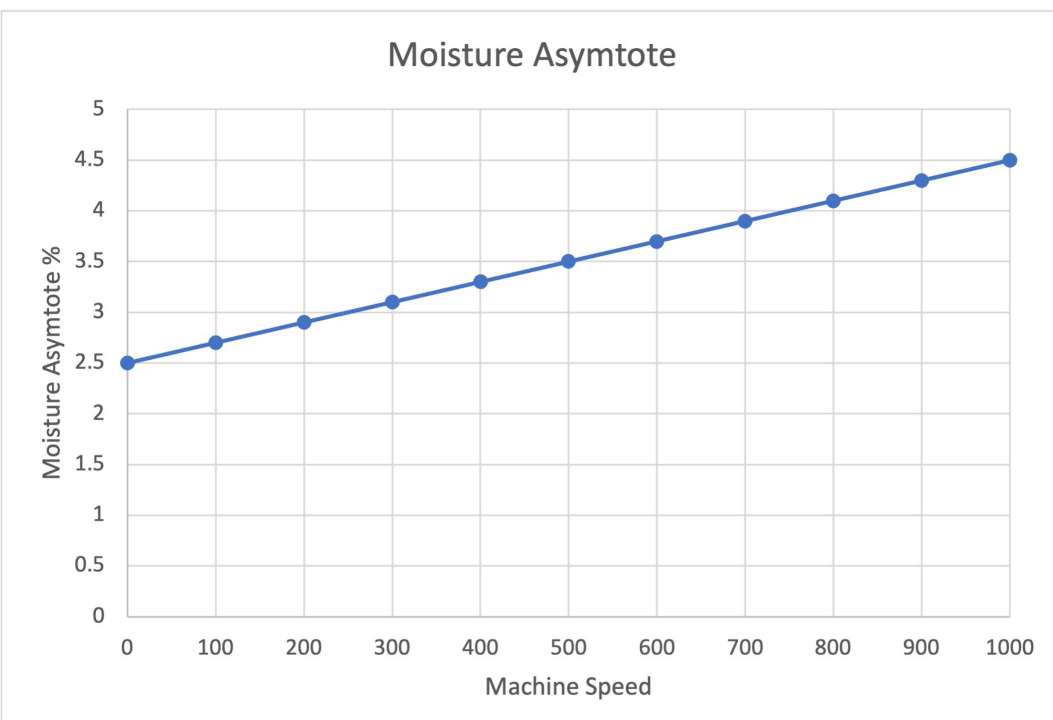
$$WaterToDryers\left(\frac{lb}{min}\right) = WaterToPress\left(\frac{lb}{min}\right) * PressDrainage\%$$

This now allows us to calculate the incoming moisture content to the dryers:

$$MoistureToDryers\% = \frac{WaterToDryers}{FiberToHeadbox}$$

We will assume if machine speed is 0 FPM (the drying time is infinite), we cannot physically reduce moisture below 2.5%, regardless of the amount of steam applied We will assume at 1000 FPM, we cannot physically reduce moisture below 4.5%. We will assume this relationship, which yields the asymptote for calculating final moisture, is linear:

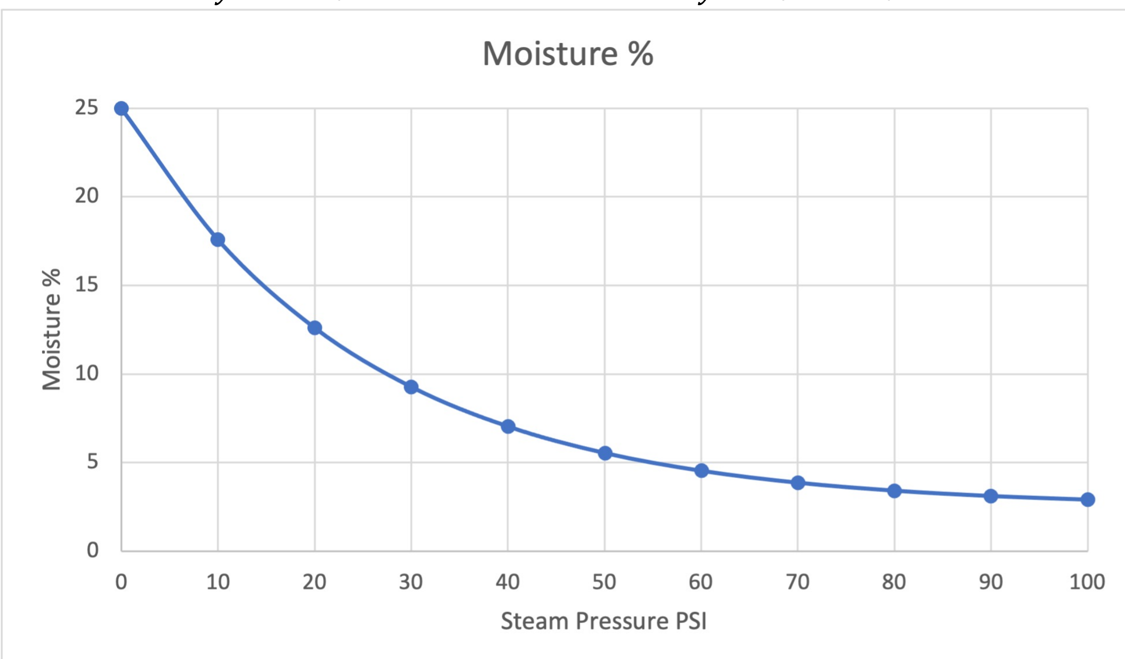
$$MoistureAsymtote\% = 2.5 + \frac{MachineSpeed}{500}$$



We now have a curve that can calculate final moisture to begin with the moisture leaving the press and not to go below the asymptote:

$$Moisture\% = MoistureToDryers\% - (MoistureToDryers\% - MoistureAsymtote\%) * \left(1 - \frac{1}{e^{Steam}}\right) = MoistureAsymtote\% + \frac{MoistureToDryers\% - MoistureAsymtote\%}{e^{\frac{Steam}{25}}}$$

For $MoistureAsymtote\% = 2.5$ and $MoistureToDryers\% = 25\%$



Dynamic response of Moisture at reel to Steam:

- Deadtime: 0.1 minutes
- Time Constant 1: 0.5 minutes
- Time Constant 2: 0 minutes

3.2. Weight

From the moisture calculations, weight is a simple mass balance

$$BonedryWeight\left(\frac{lb}{ream}\right) = FiberToHeadbox\left(\frac{lb}{min}\right) * \frac{3300(\frac{ft^2}{ream})}{WireSpeed\left(\frac{Ft}{\min}\right) * Trim(Ft)}$$

$$BasisWeight = BonedryWeight * \left(1 + \frac{Moisture}{100}\right)$$

Dynamic response of BoneDryWeight at reel to FiberToHeadbox:

- Deadtime: 5 minutes
- Time Constant 1: 15 minutes
- Time Constant 2: 5 minutes

3.3. Caliper

Caliper at the reel will be a function of the following variables:

- Basis Weight
- Press Load

We will use only press load and not complicate it by including a calendar stack. The calendar would have the same effect as the press, so I will just account for the press.

We will have a maximum caliper as at a press load of 0 and minimum caliper that is the asymptote for maximum press load. The maximum will be a function of basis weight in a linear relationship. Minimum caliper is some fixed fraction of maximum caliper. The units for caliper will be thousandths of an inch (mils).

$$CaliperMax(mils) = BasisWeight * CaliperMaxFactor$$

A reasonable value for CaliperMaxFactor is 0.1

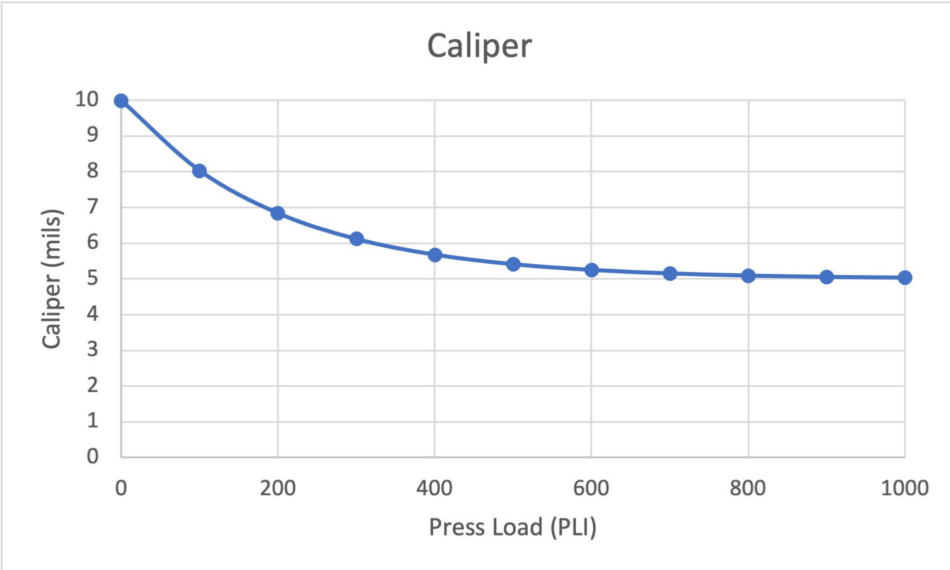
$$CaliperMin(mils) = CaliperMax * CaliperMinFactor$$

A reasonable value for CaliperMaxFactor is 0.5

The caliper will then be a function of press load as an exponential relationship with CaliperMin as the asymptote:

$$Caliper(mills) = CaliperMin + \frac{CaliperMax - CaliperMin}{e^{\frac{PressLoad}{200}}}$$

For CaliperMax of 10 mils:



4. Quality lab results

Below are the quality properties than cannot or are not measured online, and therefore need to be predicted to yield online values.

Jet to Wire is not being used as an input to these models. Although it affects MD versus CD properties, we are not going to make it more complicated by accounted for directionality.

The general approach for all lab measurements is to apply a range to each input and a gain that adds up to 100% contribution for all inputs. This will result in the calculation of a Weighted Input, which will be used as follows:

$$LabResult = LabMin + (LabMax - LabMin) * WeightedInput$$

The Weighted Input is an approximated first principles derived factor. There are no known means of applying first principles, in a strict sense, to calculate strength properties. There are too many unknowns in the physics and chemistry to make such calculations. However, we do know the direction, nature, and relative magnitudes of such relationships. These are illustrated below:

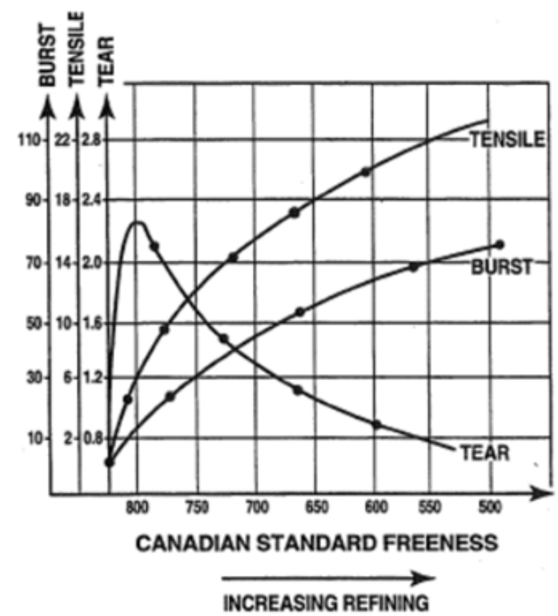


Fig. 1.16. Influence of refining on paper properties (from Handbook for Pulp and Paper Technologists by G. A. Smook)

Independent Variables

	Increased Moisture Content	Increased Refining	Increased Pressing	Increased Surface Size	Increased Calendering	Increased Long Fiber-to-Short Fiber Ratio	Increased Basis Weight	Increased Titanium Dioxide
Tensile Strength	-	+	+	+	0	+	+	-
Tearing Resistance	+	-	-	-	0	+	+	-
Bursting Strength	-	+	+	+	0	+	+	-
Folding Endurance	+	+	+	+	0	+	+	-
Stiffness	-	∓[a]	∓[a]	+	-	+	+	-
Opacity	0	-	-	-	0	-	+	+
Brightness	0	0	0	0	0	0	0	+
Thickness	+	-	-	0	-	+	+	0
Water Permeability	0	0	-	+	0	0	-	-
Air Permeability	-	-	-	-	-	+	-	-
Oil Permeability	-	-	-	-	-	+	-	-
Smoothness	-	+	+	+	+	-	0	-

[a]The affects on stiffness of pressing and refining cannot be predicted. Both lead to increased interfiber bonding and decreased thickness, which have opposing influences on stiffness.

Figure 7.18. Qualitative interrelationships between paper properties. The plusses, minuses and zeros indicate increases, decreases and no change, respectively, in the dependent paper properties as a result of a change in the papermaking process or paper components. The table refers to a single grade of paper. Only small changes in the independent variables are intended. The qualitative relationships that exist between common paper properties can be observed by studying the changes indicated within a given column.

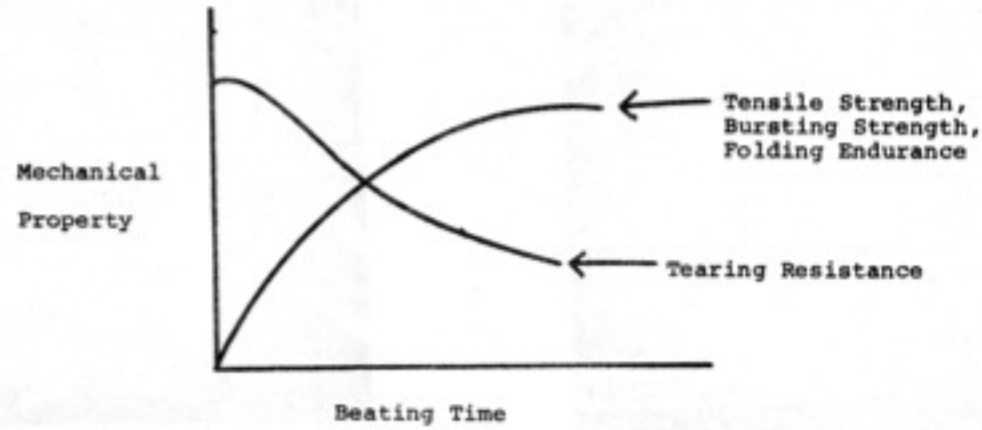


Figure 7.12 Effect of beating on the mechanical properties of paper. The plot illustrates the point that tearing strength is decreased by beating while tensile strength, bursting strength and folding endurance all increase up to a point. Consequently, the papermaker must strike a compromise between the levels of these mechanical properties that he achieves in his product.

1. Fiber shortening.

2. Removal of layers of fibrils from the outer part of the fiber wall with the formation of fines.

3. Roughening and loosening of the fiber surface -- referred to as fibrillation.

4. Breaking of intra-fiber bonds between various fiber wall layers with their replacement by water molecules within the fiber wall. This leads to a swelling and plasticizing of the fiber.

Figure 7.13 Major effects of beating and refining on fiber morphology.

From these fundamental relationships, we can approximate the gain sensitivities of each input to the lab property. The summation of these sensitivities, weighted to add up to 100% contribution, is the Weighted Input.

The factors that determine the sensitivity for each input are:

- Weight: A percentage contribution of each input, which must add to 100% for all inputs in the prediction.

- Asymtote: The maximum or minimum value that an exponential gain can represent. It is the engineering range of the input for the appropriate extremity
- Order: This is the order of the sensitivity plot.
  - 0 order (linear)
  - 1^{st} order
  - 2^{nd} order
- Slope: This allows specification of how aggressive the sensitivity plot is
- Direction: A positive (+) direction has the gain increase as the input increases. A negative (-) does the opposite.
- Upper: This specifies whether we have an gain that represents a maximum asymptote or minimum asymptote.

These factors are used as follows to calculate a Lab Result Factor as follows:

If Order not 2 and Direction > 0, Asymtote = Max
If Order not 2 and Direction < 0, Asymtote = Min

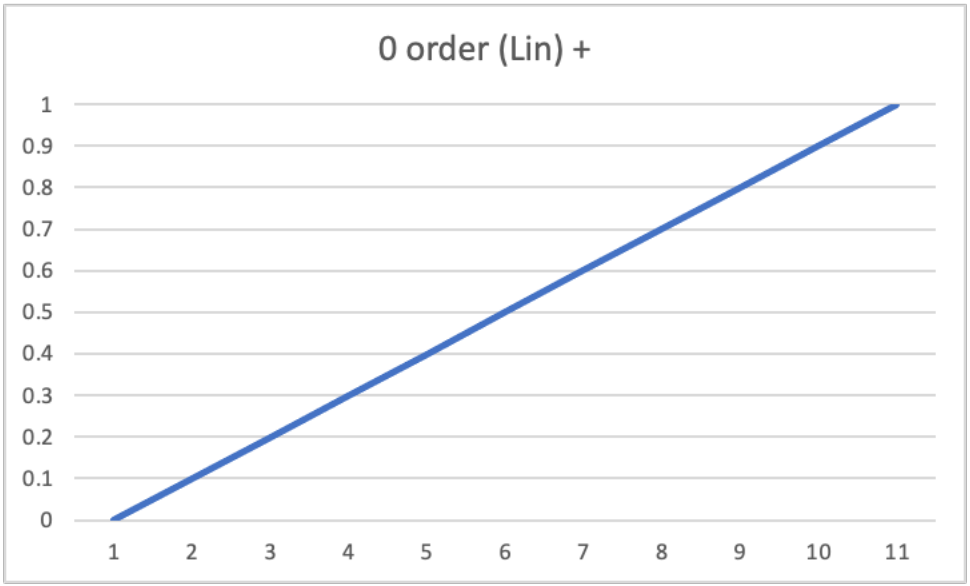
If UpperGain is false:

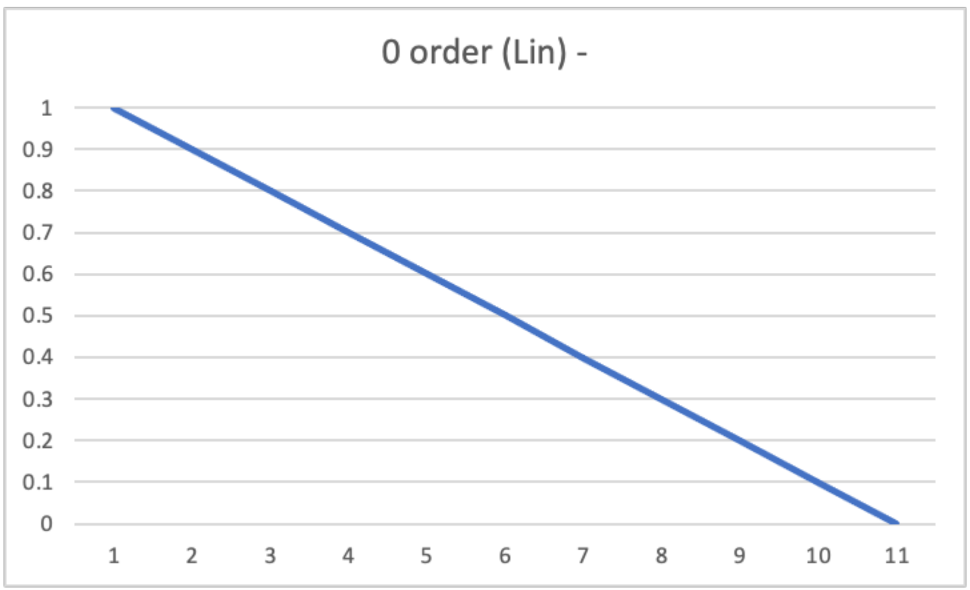
$$LabResultFactor = e^{Slope*Direction\left(\frac{Input-Asymtote}{InputMax-InputMin}\right)^{Order}}$$

else

$$LabResultFactor = 1 - e^{Slope*Direction\left(\frac{Input-Asymtote}{Max-Min}\right)^{Order}}$$

The resulting Lab Result Factor will be a value scaled between 0 to 1 as follows for each case:


0 order (Lin) +
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11


0 order (Lin) -
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11


1st order, +
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
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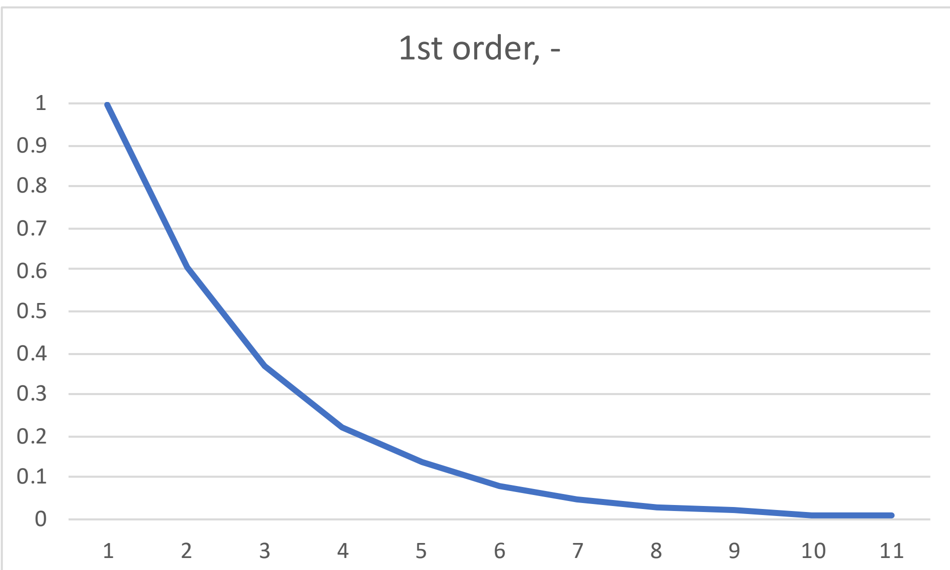
10
11


1st order, -
1
0.9
0.8
0.7
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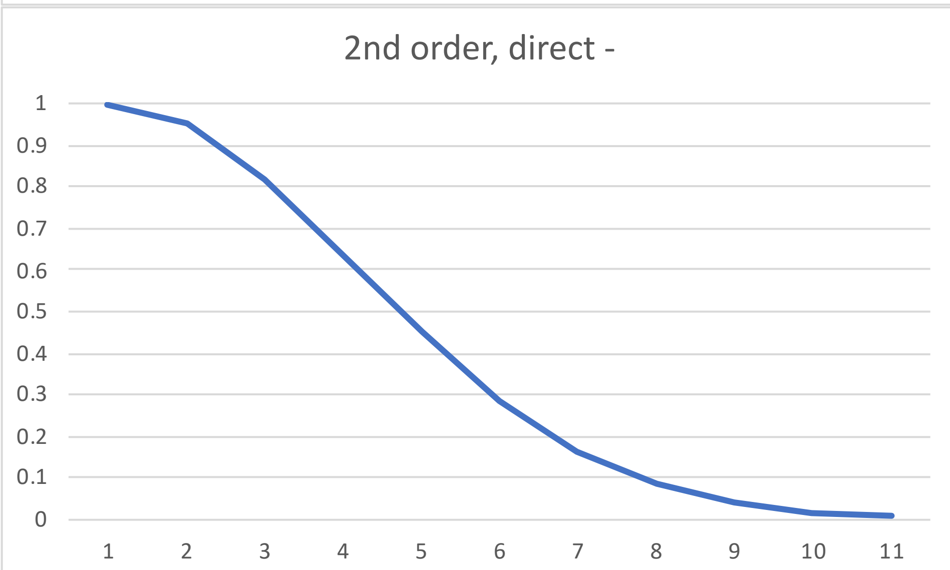
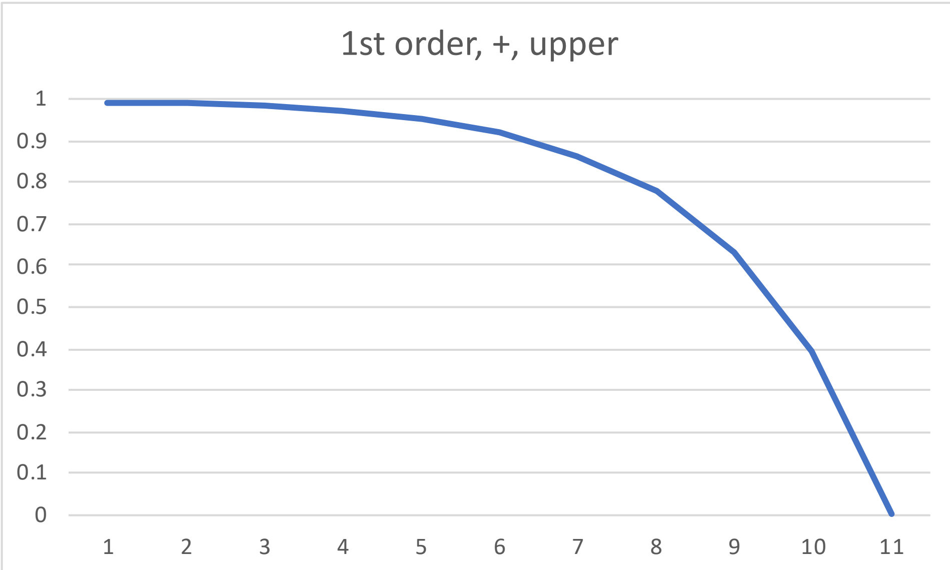
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
11


2nd order, direct +
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11


2nd order, direct -
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11


1st order, +, upper
1
0.9
0.8
0.7
0.6
0.5
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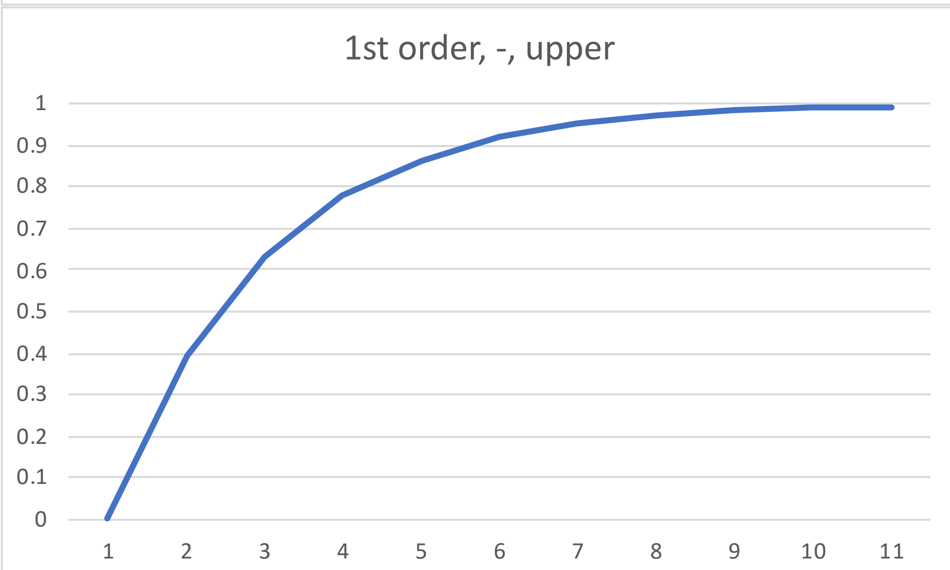
1st order, -, upper
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
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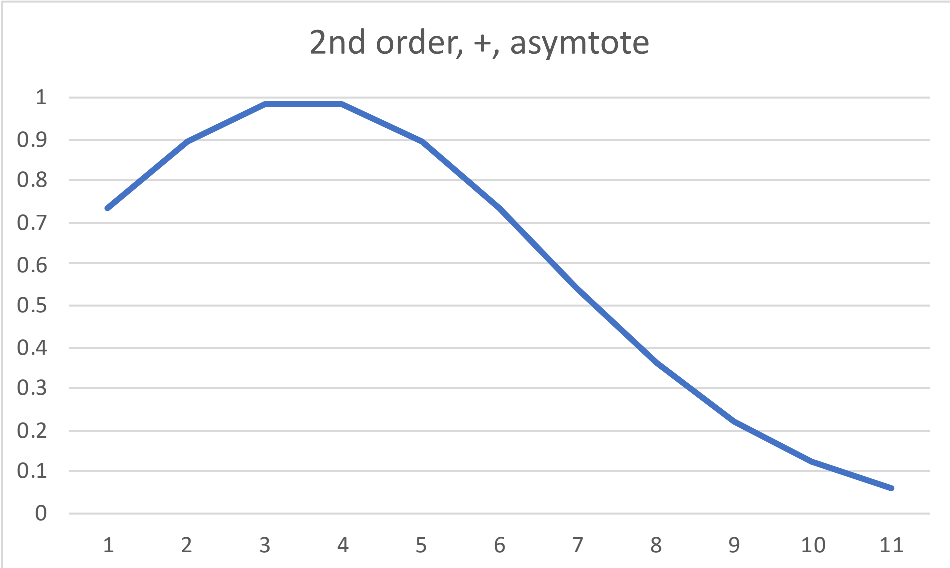

When we use these sensitivities for each input, then multiply by a weighting factor, the summation of this calculation is a Weighted Input that has a minimum of 0 and a maximum of 1. This is calculated as:

$$WeightedInput = \sum_{n=1}^{NumInputs} InputWeight_n * LabResultFactor_n$$

$$100\% = \sum InputWeight$$

We then get the calculated lab value as:

$$LabResult = LabMin + (LabMax - LabMin) * WeightedInput$$

Below are examples of lab measurements and the factors for each

4.1. Tensile

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	10		1	1	-1	
MV_PressLoad	10		1	1	1	
PulpEye_BlendFiberLength	10		1	1	1	
PulpEye_BlendShiveCount	5		1	1	-1	
PulpEye_DirtCount	5		1	1	-1	
MV_SWPct	5		1	1	1	
MV_OCCPct	5		1	1	-1	
QCS_BasisWeight	10		0	1	1	
QCS_Moisture	10		1	1	-1	

PulpEye_BlendFreeness	10		1	1	-1	
PulpEye_BlendCrill	20		1	1	1	

4.2. Tear

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	10		1	1	-1	
MV_PressLoad	10	600	2	1	1	
PulpEye_BlendFiberLength	5		1	1	1	
PulpEye_BlendShiveCount	5		1	1	-1	
PulpEye_DirtCount	5		1	1	-1	
PulpEye_Kappa	5		1	1	-1	
MV_SWPct	5		1	1	1	
MV_OCCPct	5		1	1	-1	
QCS_BoneDryWeight	10		1	1	1	
QCS_Moisture	10		1	1	-1	
PulpEye_BlendFreeness	20	750	2	1	-1	
PulpEye_BlendCrill	10	100	2	1	1	

4.3. Fold

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	5		1	1	-1	
PulpEye_BlendFiberLength	5		1	1	1	
PulpEye_BlendShiveCount	5		1	1	-1	
PulpEye_DirtCount	5		1	1	-1	
PulpEye_Kappa	5		1	1	-1	
MV_SWPct	5		1	1	1	
MV_OCCPct	5		1	1	-1	
QCS_BoneDryWeight	25		1	1	1	
QCS_Moisture	10		1	1	1	
QCS_Caliper	15		1	1	1	
PulpEye_BlendFreeness	5		1	1	-1	
PulpEye_BlendCrill	10		1	1	1	

4.4. Stiffness

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	10		1	1	-1	
PulpEye_DirtCount	10		1	1	-1	

QCS_BoneDryWeight	25		1	1	1	
QCS_Moisture	10		1	1	-1	
QCS_Caliper	25		1	1	1	
PulpEye_BlendFreeness	10		1	1	1	
PulpEye_BlendCrill	10		1	1	1	

4.5. Burst

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	5		1	1	-1	
MV_PressLoad	5		1	1	1	1
PulpEye_BlendFiberLength	5		1	1	1	1
PulpEye_BlendShiveCount	5		1	1	-1	
PulpEye_DirtCount	5		1	1	-1	
PulpEye_Kappa	5		1	1	-1	
MV_SWPct	5		1	1	1	1
MV_OCCPct	5		1	1	-1	
QCS_BasisWeight	20		1	1	1	1
QCS_Moisture	10		1	1	-1	
PulpEye_BlendFreeness	15		1	1	1	1
PulpEye_BlendCrill	15		1	1	1	1

4.6. Ring Crush

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_SWPct	10		1	1	1	1
QCS_BoneDryWeight	50		1	1	1	1
QCS_Moisture	5		1	1	-1	
QCS_Caliper	25		1	1	1	1
PulpEye_BlendFreeness	5		1	1	1	1
PulpEye_BlendCrill	5		1	1	1	1

4.7. Brightness

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	40		1	1	1	1
PulpEye_Brightness	40		1	1	1	1
PulpEye_Kappa	20		1	1	-1	

4.8. Opacity

INPUT	Weight	Asymtote	Order	Slope	Direction	Upper
MV_FillerFlow	50		1	1	1	1
QCS_BasisWeight	50		1	1	1	1