

# Optimization of Process Parameters using Desirability Concept in Conjunction with Six Sigma Process Capability Analyses-A Case Study

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## Abstract

Proven statistical techniques to measure, specify and record optimize quality have long been used in paper industry for testing theoretical hypothesis or measure and optimize process parameters. Process optimization concerned with several responses is usually reduced to the optimization procedure utilizing one criterion with equality and inequality constraints. Depending on the shape of the response surface and character of the constraints there exists a series of optimization methods such as Lagrange Multipliers, Linear and Non- Linear programming, Ridge Analysis etc. These methods are disadvantageous in that the associated computations are very complicated. A useful approach to the optimization of process with several responses is the concept of Desirability  $d$ . The concept of Desirability in conjunction with Six Sigma Process Capability Analysis proved useful to develop new quality and to optimize the process parameters. The concept of Desirability proved useful to develop a dimensionless scale to which the physical variables of paper as a commercial product are transformed. It could be a way to ascertain best commercial quality of paper.

## INTRODUCTION

Quality this day is customer's orientation. It is at best the customer actually experiences with the product he or she buys according to the requirements. The concept of desirability has proved useful in optimizing quality parameters and in development of new quality. For a commercial product like paper where large number of attributes and variables define the product and where the customer is looking for quality parameters like Tear, Tensile, Burst and Breaking Length as strength properties; Bulk, Cobb, Smoothness etc. as surface properties and Brightness, Opacity as optical properties Desirability and Cp Analysis (as both the normal curve and desirability curve exhibit the properties of an exponential relationship) can be used to optimize these physical properties to attain customer desirable quality.

## EXPERIMENTAL

### The desirability concept

Although many such scales are possible a useful scale ranges between 0.00 to 1.00 such that

$d = 0.00$  corresponds to a completely unacceptable level of quality of the product and  $d = 1.00$  corresponds to a completely acceptable level of quality, i.e. an improvement in quality would serve no purpose. The demensionless scale of  $d$  has the following tabulated scale for interpreting the quality level:

Desirability value	Description of quality level
0.80 - 1.00	Acceptable & excellent
0.63 - 0.80	Acceptable & good
0.37 - 0.63	Acceptable but poor
0.20 - 0.37	Borderline
0.0 - 0.20	Unacceptable

### Calculation of desirability

The desirability  $d$  for cases with two sided specifications can be calculated using the following equations.

$$d = \text{Exp} [ly'l]^n \dots\dots\dots(1A).$$

$$y' = \{2y - (y_{\max} + y_{\min})\}/(y_{\max} - y_{\min}) \dots\dots\dots (1B).$$

$$n = \text{Log}_e [\text{Log}_e(1/d)]/\text{Log}_e(ly'l) \dots\dots\dots(1C).$$

The exponent  $n$  may be calculated by selecting a

Table 1. Physical properties of cream wave (NB) 57 gsm

Substance gm/m <sup>2</sup>	Burst Factor	Tensile		B. length (mt)		Cobb 60	Brightness	Opacity	Tear (Avg.)	Ash %	Caliper	Bulk	Smoothness
		MD	CD	MD	CD	gm/m <sup>2</sup>	(%)	(%)			micron	cc/gm	sec/50ml
56.6	18	3.5	2.1	4020	2410	24	83.3	86.4	56	10	77	1.29	32/35/30
56.7	18	3.4	2.3	3970	2690	25	83.5	86.1	56	12	73	1.29	30/34/31
58.1	21	3.5	1.9	4090	2225	24	83.2	88.2	59	11	73	1.29	32/35/34
56.4	20	3.2	1.9	4150	2435	27	83.2	88.5	55	10	72	1.28	35/38/36
57.9	21	4.2	2.2	4740	2490	25	83.9	89.9	55	12	74	1.28	34/37/35
57.3	19	3.8	2.1	4220	2340	24	83.3	87.8	50	13	75	1.2	30/33/31
57.6	21	3.7	2	4325	2220	23	83.6	87.5	49	10	76	1.31	32/35/33
57	21	3.5	1	4090	2250	26	84.1	87.9	54	12	69	1.32	30/35/31
56.8	21	3.7	1.9	4330	2245	27	84.4	88	52	11	75	1.3	28/32/30
57.7	21					26	84.2	89	60	11		1.31	
58.5	21					27			59			1.28	
57.2	21					26			53			1.29	
56.8	22					29			52			1.27	
56.9	23					27			54			1.33	
57.6	19					26			53			1.32	
57.3	19					25			54			1.32	
56.4	21					28			51			1.33	
57.6	19					29			53			1.34	
56.7	21					28			52			1.29	
56.8	21					26			50			1.28	
56.7	19								50				
57.5	19												
57	19												

value of  $y = d$  (preferably in the range  $0.60 < d < 0.90$ ) finding the corresponding  $y'$  and substituting in the equation (1C). This is the case where two sided specifications exist for  $T_e$  property. In case of one sided specifications such as  $y < y_{\max}$  or  $y > Y_{\min}$  one can utilize another exponential relationship to transform  $y$  into  $d$  where

$$d = \text{Exp} [- \text{Exp} (y')] \dots \dots \dots (2A).$$

$$Y' = b_0 = b_1 * y \dots \dots \dots (2B).$$

The two constants  $b_0$  and  $b_1$  are determined by assigning to two values of  $y$  the corresponding values of  $d$  (preferably in the range  $0.20 < d < 0.80$ ). Having transformed the several measure of quality to the dimensionless scale of  $d$ , it is now possible to combine several  $ds$  by any of the operations of arithmetic to measure the overall desirability  $D$ , of the product. A basic premise is

this – if any one property is so poor that the product is not suitable to the application that product will not be acceptable ( $D = 0$ ).

$$D = d_1 * d_2 * d_3 \dots \dots \dots d_k^{1/k} \dots \dots \dots (3A).$$

#### Concept of six sigma process capability (Cp)

Process Capability is defined as the quality performance capability of a process during normal in control conditions. In general the process capability of a process or an output parameter is measured by process capability index  $C_p$ .

$$C_p = (\text{Upper Specification Limit} - \text{Lower Specification Limit}) / 6 * (\text{SIGMA})$$

where Sigma is the standard deviation.

In any case for a process parameter to be desirable and having adequate normal distribution the  $C_p$  values lies between  $1.33 < C_p < 1.67$ . This is an

Table 2. Calculated desirability values W.R.T. physical properties of cream wove (NB) 57 gsm

Substance gm/m <sup>2</sup>	Bulk cc/gm	Burst factor	Breaking length (mts) (mts)		Brightness (%)	Opacity (%)	COBB 60 gm/m <sup>2</sup>	Tear	Smoothness sec/50ml
56.7/0.998	1.29/0.47	18/0.2	4020/0.24	2410/0.58	83/4/0.56	88.2/0.78	24/0.84	56.09	32/0.49
58.1/0.884	1.28/0.44	21/0.45	3970/0.19	2690/0.90	83.3/0.52	86.4/0.32	25/0.80	59/0.95	30/0.20
56.4/0.985	1.2/0.18	20/0.36	4090/0.33	2225/0.20	82.5/0.20	86.1/0.20	26/0.73	55/0.875	35/0.82
57.9/0.94	1.32/0.61	10/0.27	4150/0.41	2435/0.63	83.2/0.482	88.2/0.78	27/0.67	50/0.63	34/0.74
57.3/0.998	1.3/0.5	23/0.62	4740/0.89	2490/0.71	83.9/0.72	88.5/0.83	28/0.58	49/0.55	31/0.33
57.6/0.985	1.31/0.53		4220/0.50	2340/0.44	83.3/0.52	89.9/0.95	29/0.48	54/0.84	38/0.94
57/1.00	1.27/0.4		4325/0.62	2220/0.20	83.6/0.63	87.8/0.7		52/0.755	36/0.88
56.8/0.9996	1.33/0.59		4330/0.625	2250/0.25	84.1/0.77	87.5/0.62		60/0.963	37/0.74
57.7/0.974	1.34/0.62			2245/0.245	84.4/0.83	87.9/0.72		53/0.80	30/0.2
58.5/0.694					84.2/0.79	88/0.74		51/0.7	33/0.63
57.2/0.9996						89/0.88			
56.8/0.9996									
56.9/0.99972									
57.6/0.9985									
57.3/0.9986									
56.4/0.985									
57.6/0.985									
56.7/0.9986									
56/0.99968									
56.7/0.9986									
57.5/0.9922									
56.6/0.996									

Table 3. Comparative properties against desirability values cream wove (NB) 57 gsm

	Optimum	d=1.0	d=0.9	d=0.8	d=0.75	d=0.7	d=0.63	d=0.6	d=0.5	d=0.37
Substance (gm/m <sup>2</sup> )	57.45	57	57.94	58.28	58.44	58.6	58.8	58.9	55.05	NA
Bulk (cc/gm)	1.27	1.66	1.49	1.42	1.39	1.37	1.34	1.33	1.3	1.26
Burst Factor	20.5	29.68	27.23	25.45	24.7	24	23.1	22.7	21.6	20.11
Breaking length (md)	4355	4877.6	4702.8	4564.2	4471	4409	4335	4306	4220	4142
CD	2455	3332.2	2689.6	2562.3	2548.4	2507	2457	2437	2378	2308
Tear Factor	54.5	66	56	52.95	52	51.05	50	49.6	48.37	NA
COBB 60	26	21.92	23.23	24.63	25.818	26.5	27.3	27.7	28.86	30.6
Brightness (%)	83.45	87.7	84.89	84.24	85.6	85.4	85.2	85.1	84.9	84.6
Opacity %	88	92.44	89.17	88.33	88	87.8	87.5	87.4	87	86.6
Smoothness (sec/50ml)	34	50	36.5	34.73	34.1	33.6	33	32.8	32.1	31.2

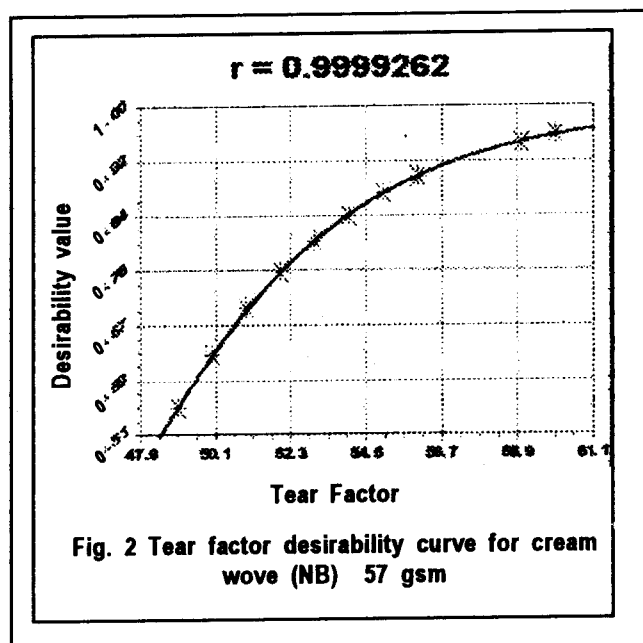
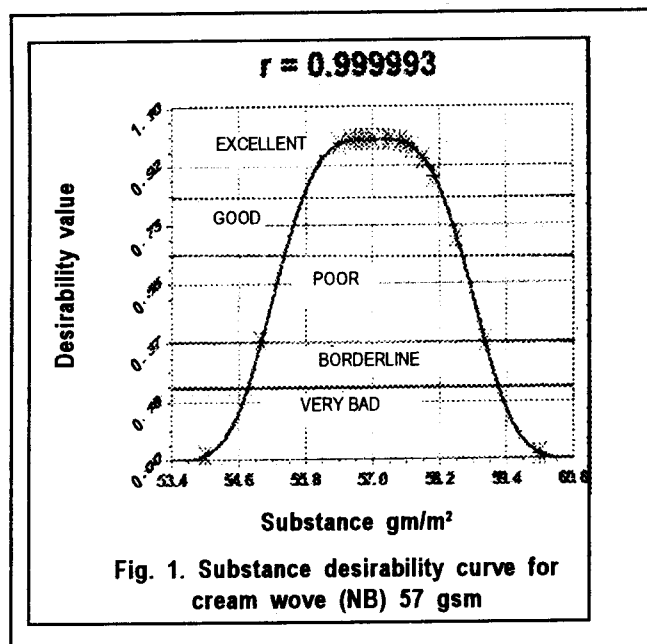


Table 4. Calculated tolerances and Cp values cream wave (NB) 57 gsm

Parameter	Mean	Std. Dev	Tolerance	Specification	Target Nominal	Cp
Substance (gm/m <sup>2</sup> )	57.9	0.55	55.0 to 59.0	+ - 2.0	57	1.21
Burst Factor	20.1	1.32	16.58 to 23.62	16.0 (min)	20.1	0.89
Tensile Strength	2.89	0.82	0.55 to 5.23	N.A.	2.89	0.95
Cobb 60 (gm/m <sup>2</sup> )	26.3	1.72	22 to 31	30 (max)	26.3	0.87
Opacity (%)	87.93	1.12	84.00 to 92.00	85 (Min)	88	1.2
Tear Factor	53.7	3.09	45 to 62	45 (Min)	53.5	0.92
Ash (%)	11.2	1.03	7.7 to 14.7	5.00 (Min)	11.2	1.13
Caliper (microns)	73.8	2.39	65.4 to 82.2	N.A.	73.8	1.2
Bulk (cc/gm)	1.296	0.03	1.216 to 1.376	1.30 (Min)	1.296	0.89
Smoothness (sec/50ml)	32.9	2.5	26.4 to 39.4	30 (Min)	32.9	0.87
Brightness (%)	83.57	0.58	81.75 to 85.22	82 (min)	83.5	1.08

Table 5. Simulated values of properties of cream wave (NB) 57 gsm against possible desirability values.

Desirability value	gsm gm/m <sup>2</sup>	Bulk cc/gm	BF mts	BI (MD) mts	BL (CD) %	Bright %	Opact %	Cobb gm/m <sup>2</sup>	Tear factor	Smoothness sec/50ml
1	57	1.72	29.67	-	3338	88.34	92.11	12.4	66	42.2
0.9	58.05	1.5	27.22	4770	2690	85	89.2	22.42	56	36.5
0.8	58.3	1.42	25.45	4545.2	2562	84.24	88.33	24.9	53	34.7
0.7	58.5	1.37	24	4409	2482	83.8	87.8	26.5	51	33.6
0.63	58.6	1.34	23.1	4335	2438	83.6	87.5	27.4	50	33
0.6	58.65	1.332	22.73	4307	2368	83.5	87.4	27.42	49.6	32.7
0.5	58.8	1.3	21.57	4220	2360	83.2	87	28.8	48.4	32
0.4	58.95	1.27	20.44	4142	2320	83	86.7	29.8	=	31.4
0.37	59	1.26	20.11	4119	2306	82.9	86.6	30	=	31.2

Table 6. Simulated desirability values W.R.T. possible values of properties of cream wove (NB) 57 gsm

gsm/d <sub>gsm</sub>	Bulk/d <sub>bulk</sub>	BF/d <sub>BF</sub>	BL(MD)/d <sub>BL</sub>	BL(CD)/d <sub>BL</sub>	Bright/d <sub>B</sub>	Opac/d <sub>Op</sub>	Cobb/d <sub>C</sub>	Tear/d <sub>Tear</sub>	D Ratings
55/0.37	1.27/0.40	16/0.1	3900/0.11	2000/0.002	82/0.05	82.0/0.02	22/0.91	45/0.2	0.10 Unacceptable
55.5/0.69	1.28/0.44	17/0.13	4000/0.20	2100/0.037	82.5/0.2	85.5/0.076	23/0.88	46/0.28	0.20 Borderline
56/0.92	1.29/0.47	18/0.19	4100/0.34	2200/0.16	83.0/0.40	86.0/0.18	24/0.84	47/0.37	0.37 Borderline
56.5/0.992	1.30/0.5	19/0.27	4200/0.47	2300/0.36	83.5/0.60	86.5/0.33	25/0.80	48/0.47	0.50 Poor
57/1.00	1.31/0.53	20/0.36	4300/0.59	2400/0.56	84.0/0.74	87.0/0.50	26/0.73	49/0.55	0.59 Poor
57.5/0.992	1.32/0.56	21/0.44	4400/0.69	2500/0.72	84.5/0.85	87.5/0.63	27/0.66	50/0.63	0.67 Acceptable
58/0.92	1.34/0.62	22/0.53	4500/0.77	2600/0.84	85.0/0.91	88.0/0.82	28/0.57	51/0.70	0.72 Good
58.5/0.69	1.35/0.65	23/0.62	4700/0.87	2700/0.9	86.0/0.97	88.5/0.82	29/0.48	52/0.75	0.76 Good
59/0.37	1.36/0.67	24/0.7	4800/0.90	2800/0.95	86.5/0.82	89.0/0.88	30/0.37	53/0.8	0.85 Good
59.5/0.112	1.37/0.7	25/0.77	5000/0.95	2900/0.97	87/1.00	89.5/0.93		54/0.84	0.85 Excellent
60/0.016	1.38/0.72	26/0.83		3000/0.98		90.0/0.95		55/0.87	0.86 Excellent
	1.39/0.74	27/0.88						56/0.90	0.90
	1.40/0.76	28/0.93						57/0.92	
	1.45/0.84							58/0.94	
								59/0.95	
								60/0.96	

Table 7. Component desirabilities; overall desirability and target optimum

d <sub>gsm</sub>	d <sub>Bulk</sub>	d <sub>BF</sub>	d <sub>BL</sub>	d <sub>Bright</sub>	d <sub>Opac</sub>	d <sub>Tear</sub>	d <sub>Smooth</sub>	d <sub>Cobb</sub>	D
0.996	0.47	0.2	0.24	0.56	0.78	0.9	0.49	0.84	0.535
0.884	0.44	0.45	0.19	0.52	0.32	0.95	0.2	0.84	0.457
0.94	0.18	0.36	0.33	0.2	0.2	0.875	0.82	0.8	0.43
0.985	0.561	0.27	0.41	0.482	0.78	0.63	0.74	0.885	0.597
0.9996	0.53	0.45	0.89	0.72	0.83	0.55	0.33	0.67	0.63
0.974	0.47	0.45	0.5	0.52	0.95	0.84	0.94	0.73	0.676
0.985	0.59	0.54	0.62	0.63	0.7	0.755	0.88	0.48	0.67
0.9986	0.561	0.62	0.33	0.77	0.62	0.963	0.74	0.73	0.673
1	0.62	0.45	0.625	0.83	0.72	0.8	0.92	0.58	0.7076*
0.985	0.561	0.27	0.63	0.79	0.74	0.84	0.63	0.58	0.64
Target 57	1.34	21	4330	84.4	87.9	53	37	28	

ideal condition and should be maintained. A process capability study should be carried out in case when the industrial distribution for a quality parameter closely resembles a normal distribution or follows a normal distribution curve pattern. The normal curve by definition is an exponential relationship and a desirability curve closely follows a normal curve distribution pattern. Century's Cream Wove (NB) a latest developed product in the notebook segment has been considered for this study. The latest concept of Six Sigma Process Capability has been used to compare the results obtained from

desirability analysis. Finally the Over All desirability concept has been used to set target optimum for the most desirable physical properties of Cream Wove (NB).

#### Case - Mat "Century's 57 gsm Cream Wove (NB) quality"

Century's Cream Wove (NB) quality is the latest developed product in the market for the Note Book Segment. Quality Control Statistics for Cream Wove (NB) was considered as depicted in Table 1. Each and every physical property e.g. substance, Cobb60,

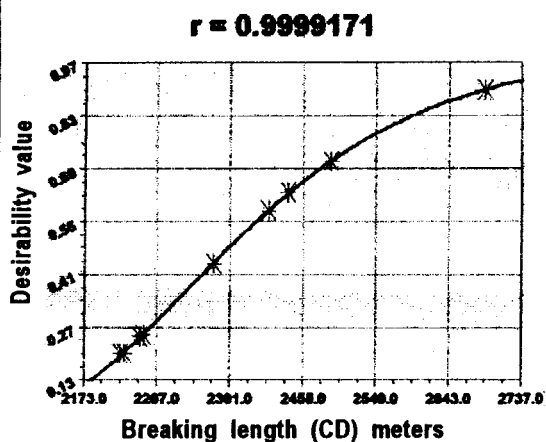


Fig. 3 Breaking length (CD) desirability curve for cream wave (NB) 57 gsm

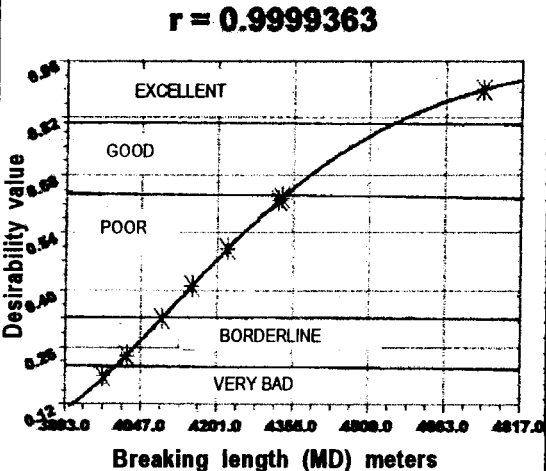


Fig. 4 Breaking length (MD) desirability curve for cream wave (NB) 57 gsm

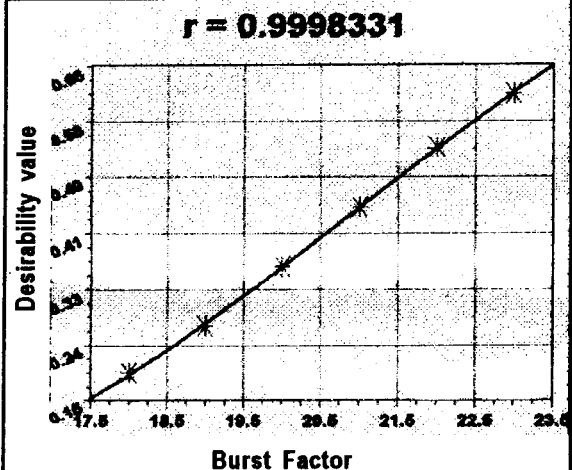


Fig. 5 Burst factor desirability curve for cream wave (NB) 57 gsm

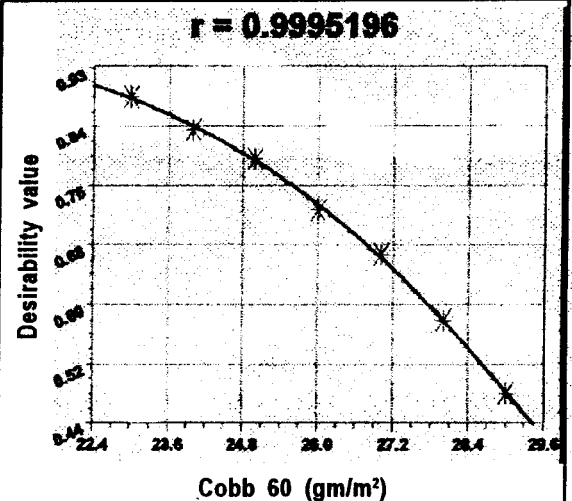


Fig. 6 Cobb60 desirability curve for cream wave (NB) 57 gsm

Tear, Brightness, Opacity, Smoothness etc. considered was subjected to desirability calculations Table 2. Further for each the desirability curves were plotted (Figs 1 to 10). Six Sigma tolerances for each of the physical parameters considered were calculated and further the Statistics were subjected to Process Capability Calculations as depicted in Table 4. For each the components Desirabilities were calculated and further the values of the physical parameters were obtained against probable desirability values, Tables 2 and 3. After obtaining the Component Desirabilities, over all Desirability for each parameter was calculated and a Target Optimum was decided, (Table 7). Further the Simulated values of physical parameters of Cream Wave (NB) 57 gsm paper were obtained with respect

to probable desirability values. Finally Simulated Values of the component desirability were obtained with respect to probable physical values. Finally Simulated Values of the component desirability were obtained using plotted graphs against probable values of the physical properties and D ratings parameters were compared, (Tables 5 and 6).

## RESULTS AND DISCUSSION

The desirability curve for substance was plotted using Table 2. The correlation coefficient for this

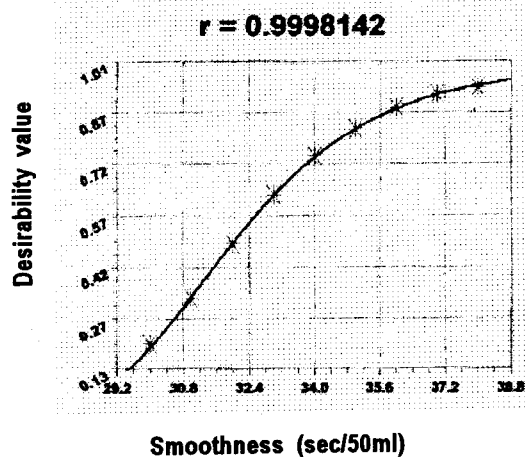


Fig. 7 Smoothness desirability curve for cream wove (NB) 57 gsm

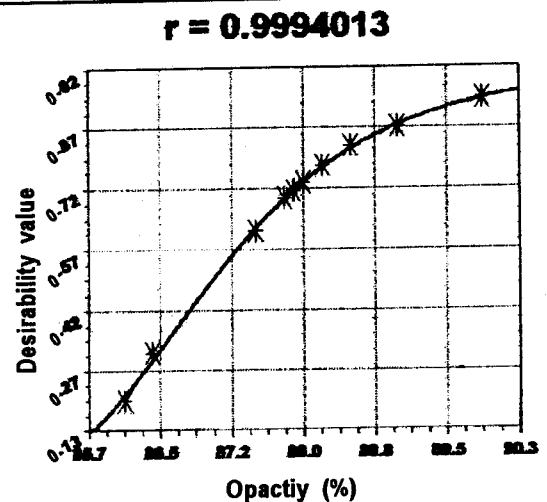


Fig. 9 Opacity desirability curve for cream wove (NB) 57 gsm

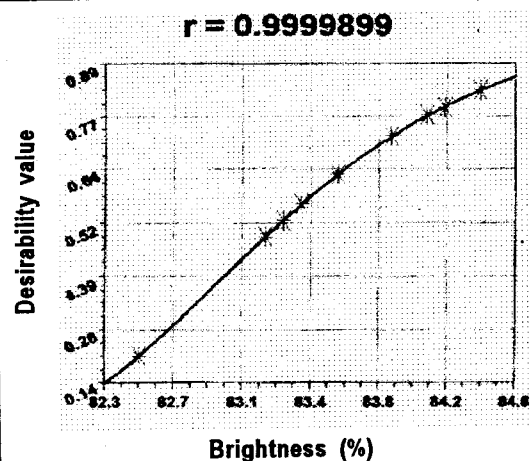


Fig. 8 Brightness desirability curve for cream wove (NB) 57 gsm

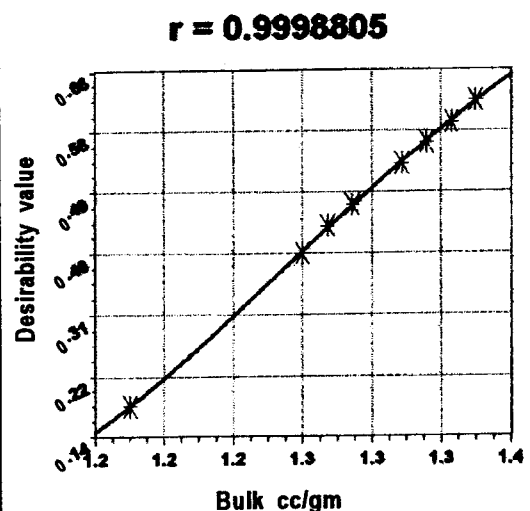


Fig. 10 Bulk desirability curve for cream wove (NB) 57 gsm

curve is 0.999993 (Fig 1). From the substance desirability curve it can be interpreted that three points lie in the unacceptable zone, two points lie at the border of Borderline and poor zone, three points lie in the poor and acceptable zone and maximum number of points lie in the excellent zone. Though the process has been subjected to a variable state few points lie out of specification and the substance desirability is at excellent quality level.

- Mean value for substance 57.2 gm/m<sup>2</sup>.
- Standard Deviation: 0.56.

- Specification: 57 + = 2.0 gm/m<sup>2</sup>.
- Calculated Tolerance: 57.2 + — 2.0 gm/m<sup>2</sup>.
- Process Capability Index (Cp): 1.21

As Cp is in the range  $1.33 < Cp < 1.00$  it indicates that though process capability is not sufficient high it is adequate. Gsm variation might result if Cp approaches 1.00. This is in conjunction with the desirability curve for substance. Though the process showed variability only a few points were close to the specification limits and maximum number of

points were within the specified tolerances.

From Breaking Length (MD) desirability curve with a correlation coefficient of 0.9999363 one point lies in the very bad and unacceptable zone one point lies in the borderline zone, four to five points lie in the poor and acceptable zone and one point lies in the Excellent zone. The calculated tolerance is  $4215.0 \pm 1709$  and the process capability index is 1.54 again indicating that process capability is sufficiently high and is an ideal condition to be maintained.

Brightness desirability curve with 0.999899 correlation coefficient reveals that one point lies in the very bad and unacceptable zone, of the points lie in the borderline zone, four points lie in the poor and unacceptable zone, three points lie in the good and acceptable zone and one point lies in the very good and excellent zone. The mill specification for brightness is 82% minimum. The calculated tolerance is  $83.63 \pm 1.88$ . The process capability index calculated is 1.08 As  $1.33 < C_p < 1.00$ , process capability is not sufficiently high but is adequate. Control of process is required and to be maintained in controlled state. Low brightness case might result if  $C_p$  approaches 1.00.

The opacity desirability curve with a correlation coefficient of 0.9994013 indicates that one point lies in the very bad and unacceptable zone, one point lies in the borderline zone one point lies in the poor zone and maximum numbers of points lie in the good excellent zone. The mill specification is 85% minimum. The calculated tolerance is  $88 \pm 4\%$ . The process capability is 1.20. As  $1.33 < C_p < 1.00$  process capability is not sufficiently high but is adequate.

Similarly the results can be interpreted for other quality parameters using the desirability curves and Table 4. The values of target optimum are seen from Table 7 and the values of best achievable commercial quality can be interpreted graphically.

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## CONCLUSION

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The desirability concept proved useful in evaluating the best achievable properties of commercial grade paper. The evaluation of Six Sigma Process Capability and desirability values can be used to optimize and control the process parameters for producing the best quality and as per customer requirements.

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