Taguchi Method Case-Study

OPTIMIZATION of ELECTRIC DISCHARGE MACHINE (EDM)

by

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COMPANY : ELECTRONICA MACHINE TOOLS, PUNE, INDIA

8 STEPS IN TAGUCHI METHODOLOGY

COMPANY : ELECTRONICA MACHINE TOOLS, PUNE

" ELECTRIC DISCHARGE MACHINE (EDM) OPTIMIZATION AND STABILIZATION "

1. IDENTIFY THE MAIN FUNCTION, SIDE EFFECTS, AND FAILURE MODE
2. IDENTIFY THE NOISE FACTORS, TESTING CONDITIONS, AND QUALITY CHARACTERISTICS
3. IDENTIFY THE OBJECTIVE FUNCTION TO BE OPTIMIZED
4. IDENTIFY THE CONTROL FACTORS AND THEIR LEVELS
5. SELECT THE ORTHOGONAL ARRAY MATRIX EXPERIMENT
6. CONDUCT THE MATRIX EXPERIMENT
7. ANALYZE THE DATA, PREDICT THE OPTIMUM LEVELS AND PERFORMANCE
8. PERFORM THE VERIFICATION EXPERIMENT AND PLAN THE FUTURE ACTION

STEPS IN TAGUCHI METHODOLOGY
COMPANY : ELECTRONICA MACHINE TOOLS, PUNE
" ELECTRIC DISCHARGE MACHINE (EDM) OPTIMIZATION AND STABILIZATION "

1. IDENTIFY THE MAIN FUNCTION, SIDE EFFECTS, AND FAILURE MODE

MAIN FUNCTION : (1) Optimize and Stabilize the EDM Performance Characteristics namely
a. Material Removal Rate (MRR)
b. Percent Electrode Wear (EW)

SIDE EFFECTS : Since this first trial application no other Quality Characteristics will be observed

FAILURE MODE : Control Factor Levels are selected so that there will not be any failure during experimentation leading to aborting an experiment

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1. IDENTIFY THE MAIN FUNCTION, SIDE EFFECTS, AND FAILURE MODE

2. IDENTIFY THE NOISE FACTORS, TESTING CONDITIONS, AND QUALITY CHARACTERISTICS

NOISE FACTORS : (1) Variations in Hardness of material
(2) Variation in Dielectric Bath temperature

TESTING CONDITIONS : Keep sparking time constant for all experiments

NOISE CAPTURING TEST CONDITIONS :

For each experiment make 4 work pieces under the following noise conditions

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1. IDENTIFY THE MAIN FUNCTION, SIDE EFFECTS, AND FAILURE MODE
2. **IDENTIFY THE NOISE FACTORS, TESTING CONDITIONS, AND QUALITY CHARACTERISTICS**

NOISE CAPTURING TEST CONDITIONS :

For each experiment make 4 work pieces under the following noise conditions

Measure MRR and EW on these 4 work pieces

Work piece No.	Noise Factors: Material	Noise Factors: Bath Temp.
1	Hard	Room Temp.
2	Soft	Room Temp.
3	Hard	High Temp.
4	Soft	High Temp.

QUALITY CHARACTERISTICS : (1) MRR (2) EW

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1. IDENTIFY THE MAIN FUNCTION, SIDE EFFECTS, AND FAILURE MODE
2. IDENTIFY THE NOISE FACTORS, TESTING CONDITIONS, AND QUALITY CHARACTERISTICS
3. **IDENTIFY THE OBJECTIVE FUNCTION TO BE OPTIMIZED**

OBJECTIVE FUNCTION :

(1) MRR ---> LARGER - THE - BETTER

$$\eta_{MRR} = -10 \, Log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y^2} \right]$$

(2) EW ---> SMALLER - THE - BETTER

$$\eta_{EW} = -10 \, Log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} y^2 \right]$$

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2. IDENTIFY THE NOISE FACTORS, TESTING CONDITIONS, AND QUALITY CHARACTERISTICS
3. IDENTIFY THE OBJECTIVE FUNCTION TO BE OPTIMIZED
4. **IDENTIFY THE CONTROL FACTORS AND THEIR LEVELS**

CONTROL FACTORS	LEVELS 1	LEVELS 2	LEVELS 3
A. PULSE ON TIME (µSec)	150	200	500
B. GAP CURRENT (Amps)	30	34	50
C. BI-PULSE CURRENT (Amps)	0	1	3

CONTROL FACTORS AND LEVELS

From excel sheet

CONTROL FACTORS	LEVELS		
	1	2	3
Pulse-On Time	150 usec	200 usec	500 usec
Gap Current	30 amp	34 amp	50 amp
Bi-Pulse Current	0 amp	1 amp	3 amp
e	e	e	e

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4. IDENTIFY THE CONTROL FACTORS AND THEIR LEVELS
5. **SELECT THE ORTHOGONAL ARRAY MATRIX EXPERIMENT**

DEGREES OF FREEDOM = 1 FOR MEAN AND 2 EACH FOR 3 FACTORS = 1+6 = 7

ORTHOGONAL ARRAYS WITH 3 - LEVEL FACTORS :

NO. OF FACTORS	2-4	5-7	8-13
ORTHOGONAL ARRAY	L9	L18	L27

⟶ **L9**

Degrees of Freedom from ADDITIVE MODEL

- **For each row of the OA (i.e. each experiment), it gives the obj. func. η in terms of overall mean μ or m, Control Factor effects a_i, b_j, c_k etc and error ϵ in each experiment**

$$\eta_n = \mu + a_i + b_j + c_k + d_l + \ldots + \epsilon$$

- **Degrees of freedom for various terms in additive model are**
  - **DF for η = number of rows of OA**
  - **DF for μ or m = 1**
  - **DF for each Control Factor A, B, C etc. = (no. of levels–1)**
    - This is because of additional constraint for each column

      a1 + a2 + a3 = 0, b1 + b2 + b3 = 0, c1 + c2 + c3 = 0 etc.
  - **This leaves DF for error** = (DF for η)-(DF for μ)-(DF for all CF)

    = (no. of rows) – (1) – (no. of CF)*(No. of CF Levels-1)

Degrees of Freedom from **ADDITIVE MODEL**

- **Degrees of freedom for the current problem are**
  - **DF for η = number of rows of OA = 9 (OA is L9)**
  - **DF for μ or m = 1 (always 1 for the overall mean)**
  - **DF for each Control Factor A, B, C etc.**

    = (no. of levels–1) = (3 -1) = 2
  - **DF for 3 Control Factors = 3 * 2 = 6**
  - **This leaves DF for error**

    = (DF for η)-(DF for μ)-(DF for all CF)

    = (no. of rows) – (1) – (no. of CF)*(No. of CF Levels-1)

    = 9 – 1 – (3 * 2) = 2

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5. SELECT THE ORTHOGONAL ARRAY MATRIX EXPERIMENT

L9 ORTHOGONAL ARRAY

EXPT. NO.	A 1	B 2	C 3	4
1	A1	B1	C1	-
2	A1	B2	C2	-
3	A1	B3	C3	-
4	A2	B1	C2	-
5	A2	B2	C3	-
6	A2	B3	C1	-
7	A3	B1	C3	-
8	A3	B2	C1	-
9	A3	B3	C2	-

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Experimenter's Log using L9 ARRAY

from Excel sheet

	Control Factors Assigned to columns			
Expt. No.	**Pulse-On Time**	**Gap Current**	**Bi-Pulse Current**	**e**
1	150 usec	30 amp	0 amp	e
2	150 usec	34 amp	1 amp	e
3	150 usec	50 amp	3 amp	e
4	200 usec	30 amp	1 amp	e
5	200 usec	34 amp	3 amp	e
6	200 usec	50 amp	0 amp	e
7	500 usec	30 amp	3 amp	e
8	500 usec	34 amp	0 amp	e
9	500 usec	50 amp	1 amp	e

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5. SELECT THE ORTHOGONAL ARRAY MATRIX EXPERIMENT
6. **CONDUCT THE MATRIX EXPERIMENT**

---> CONDUCT THE 9 EXPTS. OF L9 ARRAY

---> IN EACH EXPT. MEASURE THE MRR AND %EW FOR THE 4 NOISE CONDITIONS OF HARDNESS AND BATH TEMPERATURE

DATA for Quality Characteristics, MRR

Expt No.	4 Repetitions or Measurements for each expt.			
1	168.3	169.2	161.2	161.1
2	221.4	220.5	214.2	215.3
3	318.3	317.7	312.4	310.9
4	192.4	191.5	188.7	187.1
5	238.2	239.7	233.9	231.6
6	312.6	311.2	307.3	308
7	198.4	197.1	192.8	191.9
8	181.1	182.3	178.9	177.4
9	325.8	324.4	317.8	316.3

DATA for Quality Characteristics, EW%

Expt No.	4 Repetitions or Measurements for each expt.			
1	15.2	16.5	12.2	11.6
2	7.2	7.4	6.4	6.6
3	11.2	11.3	10.6	10.9
4	2.6	2.6	2.3	2.5
5	4.2	4.3	3.8	3.7
6	15.3	15.4	14.9	15.2
7	0.65	0.7	0.5	0.6
8	7.3	7.2	6.8	6.8
9	2	1.9	1.5	1.4

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6. CONDUCT THE MATRIX EXPERIMENT

L9 ORTHOGONAL ARRAY AND EXPERIMENTER'S LOG

EXPT. NO.	PULSE ON TIME A	GAP CURRENT B	BIPULSE CURRENT C	empty D	S / N RATIO	
					η_{MRR}	η_{EW}
1	150	30	0	-		
2	150	34	1	-		
3	150	50	3	-		
4	200	30	1	-		
5	200	34	3	-		
6	200	50	0	-		
7	500	30	3	-		
8	500	34	0	-		
9	500	50	1	-		

Calculating S/N Ratio for **MRR** "Larger-the-better"

- **Calc 1:**
  - Find the sum of squares of reciprocals of all measured values
    SSQ = Y1^-2 + Y2^-2 + Y3^-2 + Y4^-2
- **Calc 2:**
  - Find the 'mean sum of squares of reciprocals'
    MSSQ = **(SSQ)** / (number of measurements)
- **Calc 3:**
  - Take 10 Log_{10} of MSSQ to get S/N Ratio
    η = -10 * Log_{10} of **(MSSQ)**

$$\eta = -10 \ \text{Log}_{10} \left[\frac{1}{n} \sum (1/Y_1^2 + 1/Y_2^2 + \dots + 1/Y_n^2) \right]$$

Calculating S/N Ratio for **MRR** "Larger-the-better"

Expt. No.	MRR1 H1 T1	MRR2 H1 T2	MRR3 H2 T1	MRR4 H2 T2	Sum of Squares of reciprocals	Mean of Sum of Squares of reciprocals	SN Ratio (Larger-the-Better)
1	168.3	169.2	161.2	161.1	1.47E-04	3.68E-05	44.34
2	221.4	220.5	214.2	215.3	8.43E-05	2.11E-05	46.76
3	318.3	317.7	312.4	310.9	4.04E-05	1.01E-05	49.96
4	192.4	191.5	188.7	187.1	1.11E-04	2.77E-05	45.57
5	238.2	239.7	233.9	231.6	7.20E-05	1.80E-05	47.45
6	312.6	311.2	307.3	308	4.17E-05	1.04E-05	49.82
7	198.4	197.1	192.8	191.9	1.05E-04	2.63E-05	45.80
8	181.1	182.3	178.9	177.4	1.24E-04	3.09E-05	45.10
9	325.8	324.4	317.8	316.3	3.88E-05	9.71E-06	50.13

Calculating S/N Ratio for **EW%** "smaller-the-better"

- **Calc 1:**
  - Find the sum of squares of all measured values
    SSQ = Y1^2 + Y2^2 + Y3^2 + Y4^2
- **Calc 2:**
  - Find the 'mean sum of squares'
    MSSQ = **(SSQ)** / (number of measurements)
- **Calc 3:**
  - Take 10 Log_{10} of MSSQ to get S/N Ratio
    η = -10 * Log_{10} of **(MSSQ)**

$$\eta = -10 \ \text{Log}_{10} \left[\frac{1}{n} \sum (Y_1^2 + Y_2^2 \ldots + Y_n^2) \right]$$

Calculating S/N Ratio for **EW%** "smaller-the-better"

Expt. No.	MRR1 H1 T1	MRR2 H1 T2	MRR3 H2 T1	MRR4 H2 T2	Sum of Squares	Mean of Sum of Squares	SN Ratio (smaller-the-better)
1	15.2	16.5	12.2	11.6	786.69	1.97E+02	-22.94
2	7.2	7.4	6.4	6.6	191.12	4.78E+01	-16.79
3	11.2	11.3	10.6	10.9	484.30	1.21E+02	-20.83
4	2.6	2.6	2.3	2.5	25.06	6.27E+00	-7.97
5	4.2	4.3	3.8	3.7	64.26	1.61E+01	-12.06
6	15.3	15.4	14.9	15.2	924.30	2.31E+02	-23.64
7	0.65	0.7	0.5	0.6	1.52	3.81E-01	4.20
8	7.3	7.2	6.8	6.8	197.61	4.94E+01	-16.94
9	2	1.9	1.5	1.4	11.82	2.96E+00	-4.71

EXPERIMENTER'S LOG with S/N Ratios for MRR AND %EW

EXPT. NO.	PULSE ON TIME A	GAP CURRENT B	BIPULSE CURRENT C	empty D	S / N RATIO	
					MRR	%EW
1	150	30	0	-	44.34	-22.93
2	150	34	1	-	46.76	-16.78
3	150	50	3	-	49.96	-20.83
4	200	30	1	-	45.57	-7.96
5	200	34	3	-	47.45	-12.05
6	200	50	0	-	49.82	-23.63
7	500	30	3	-	45.80	4.43
8	500	34	0	-	45.10	-16.91
9	500	50	1	-	50.13	-4.62

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7. **ANALYZE THE DATA, PREDICT THE OPTIMUM LEVELS AND PERFORMANCE**

ASSUMING ADDITIVITY

FACTOR EFFECTS PLOTS

} **PREDICT** {

OPTIMUM FACTOR LEVELS

PREDICTED IMPROVEMENT

L9 ORTHOGONAL ARRAY

with MEASURED SN-RATIO

EXPT. NO.	1 A	2 B	3 C	4 D	SN-RATIO η (in dB)
1	A1	B1	C1	D1	η1
2	A1	B2	C2	D2	η2
3	A1	B3	C3	D3	η3
4	A2	B1	C2	D3	η4
5	A2	B2	C3	D1	η5
6	A2	B3	C1	D2	η6
7	A3	B1	C3	D2	η7
8	A3	B2	C1	D3	η8
9	A3	B3	C2	D1	η9

FACTOR EFFECTS for MRR

- **EFFECT OF A FACTOR LEVEL IS DEFINED AS " THE DEVIATION IT CAUSES FROM OVERALL MEAN , m "**
- **FACTOR EFFECT OF A, Pulse-On Time, LEVEL 1, 2 and 3 :**

→ A1 OCCURS IN EXPTS. 1, 2, 3, A2 in 4, 5, 6 and A3 in 7, 8 AND 9

mA1 = 1/3 * (η 1 + η 2 + η 3) = 1/3 * (44.34 + 46.76 + 49.96) = 47.02

mA2 = 1/3 * (η 4 + η 5 + η 6) = 1/3 * (45.57 + 47.45 + 49.82) = 47.61

mA3 = 1/3 * (η 7 + η 8 + η 9) = 1/3 * (45.80 + 45.10 + 50.13) = 47.01

→ FACTOR EFFECT OF A3, ‘ a3 ’ = mA3 - m and so on

- **REPEAT FOR ALL FACTORS AND ALL LEVELS**
  - **mA1 , mA2 , mB1 , ... , mD2 , mD3**

- **Overall Mean, m = 1/9 (η 1 + η 2 + . . + η 9) = 47.21**

TABULAR AND GRAPHICAL REPRESENTATION OF FACTOR EFFECTS

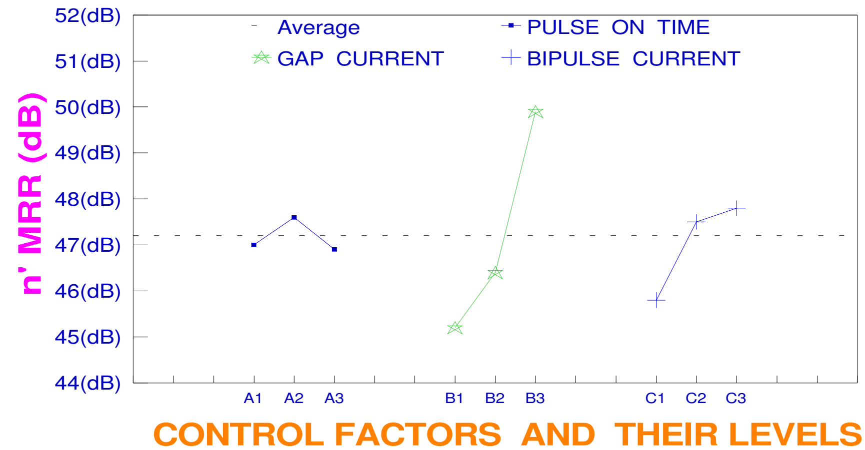
- NUMERICAL VALUES ARE GIVEN IN A TABULAR FORM

or

- GRAPHICAL REPRESENTATION IS CONVENIENT FOR DRAWING QUALITATIVE INFERENCES AND CHOOSING THE OPTIMUM LEVELS OF FACTORS **(shown in next slide)**

Plots of Factor Effects

S/N Analysis of MRR for EDM M/C



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FACTOR EFFECTS for EW%

- **EFFECT OF A FACTOR LEVEL IS DEFINED AS " THE DEVIATION IT CAUSES FROM OVERALL MEAN , m "**
- **FACTOR EFFECT OF A, Pulse-On Time, LEVEL 1, 2 and 3 :**

  → A1 OCCURS IN EXPTS. 1, 2, 3, A2 in 4, 5, 6 and A3 in 7, 8 AND 9

  mA1 = 1/3 * (η 1 + η 2 + η 3) = 1/3 * (-22.93 -16.78 – 20.83) = -20.18

  mA2 = 1/3 * (η 4 + η 5 + η 6) = 1/3 * (-7.96 – 12.05 – 23.63) = -14.54

  mA3 = 1/3 * (η 7 + η 8 + η 9) = 1/3 * (4.43 – 16.91 – 4.62) = - 5.70

  → FACTOR EFFECT OF A3, ' a3 ' = mA3 - m and so on

- **REPEAT FOR ALL FACTORS AND ALL LEVELS**

  – mA1 , mA2 , mB1 , ... , mD2 , mD3

- **Overall Mean, m = 1/9 (η 1 + η 2 + . . + η 9) = -13.47**

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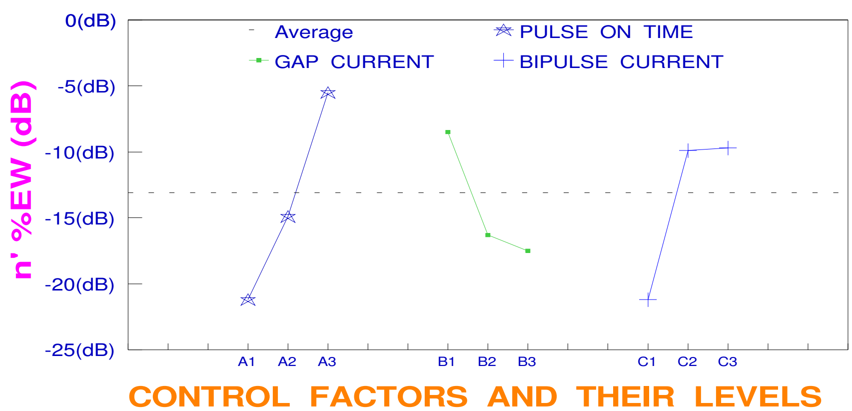
Plots of Factor Effects

S/N Analysis of %EW for EDM M/C



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Select the Best Settings

- Plot both MRR and EW% plots together
  (see next slide)
- Decide which factor *individually* 'improves' MRR
  (shown with STAR

and

- which factor would *individually* 'improve' EW%
  (shown with STAR

- Finalize Best settings as A3 B3 (C2 or C3)

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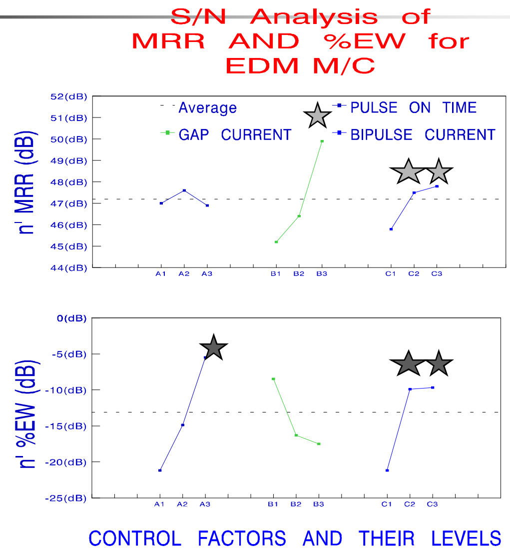
Plots of Factor Effects



Calculate the Best result for **MRR**

(For the Best Setting A3, B3, C2)

- **USE ADDITIVE MODEL AS**

$$\eta = m + a_i + b_j + c_k + \ldots + \epsilon$$

- $\eta_{MRR\ OPT}$ = m + (mA3 – m) + (mB3 – m) + (mC2 – m)

  where **'m' = 47.21** is the overall mean

- $\eta_{MRR\ OPT}$ = m + (mA3 – m) + (mB3 – m) + (mC2 – m)
- $\eta_{MRR\ OPT}$ = 47.21 + (47.02 – 47.21)+ (49.98 – 47.21)+ (47.47 – 47.21)

  = **50.05 dB**

- **MRR_{OPT} = 10^(50.05/20) = 318 gram/min**

Calculate the Best result for EW%
(For the Best Setting A3, B3, C3)

- **USE ADDITIVE MODEL AS**

$$\eta = m + a_i + b_j + c_k + \ldots + \epsilon$$

- $\eta_{\%EW\ OPT} = m + (mA3 - m) + (mB3 - m) + (mC3 - m)$

  where **'m' = -13.47** is the overall mean

- $\eta_{\%EW\ OPT} = m + (mA3 - m) + (mB3 - m) + (mC3 - m)$
- $\eta_{\%EW\ OPT} = -13.47 + (-5.70 - \{-13.47\}) + (-16.36 - \{-13.47\}) + (-9.79 - \{-13.47\})$

  $= \mathbf{-4.91\ dB}$

- $\%EW_{OPT}$ **= 10^(-4.91/-20) = 1.76 %**

PREDICTION AND VERIFICATION
MRR AND %EW for EDM Machine

	CONTROL FACTOR SETTINGS	MRR (ccm / min)		%EW	
		PREDICTED	OBSERVED	PREDICTED	OBSERVED
NOMINAL	A2 B2 C2	233	236	4.13	4.0
OPTIMUM	A3 B3 C2	318	321	1.76	1.7
% IMPROVEMENT		39%	36%	57%	57%

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RESULTS MATCH WELL WITH PREDICTION ⟶ **ADOPT NEW SETTINGS**

Thank You