Engineering Design

The engineering design process

1. Determine needs
2. Create specifications
3. Develop plan
4. Perform block design
5. Design each block
6. Select best alternatives
7. Test
8. Manufacture
9. Deliver

Step 2: Create Specification

Nonfunctional Requirements

- **Operation Environment**
  - ❑ **Temperature conditions**
  - ❑ **Humidity conditions**
  - ❑ **Lighting conditions**

Nonfunctional Requirements

- Shape, size, weight
- Reliability
- Power Supply
- Power Consumption
- Production expense
- Production time

Functional Requirements

- **Protection function:**
  - ❑ Is there any form to protect the product from water, moisture?
- **Display Function:**
  - ❑ The order of display
  - ❑ List the order of effects

Practice: Select best alternatives

Choose LEDs

Criterion	Solution A	Solution B	Solution C
Price	1000	1500	1200
Reliability	1/2	1	1
Size	to (1cm)	nhỏ (0.5)	vừa (0.7)
Appearance	good looking (3)	so so (2)	bad-looking (1)

$$\mu = \alpha * Price + \beta * Reliability + \gamma * Size + \varepsilon * Apperance$$

Normalize

Select min(muy)

Step 7: Testing

Scientific Method

- **Decide what phenomenon you wish to investigate.**

- **Specify how you can manipulate the factor**
- **Hold all other conditions fixed**

  → to insure that these extraneous conditions aren't influencing the response you plan to measure.

- **Measure your chosen response variable at several (at least two) settings of the factor under study.**

Scientific Method

- **If changing the factor causes the phenomenon to change**

  → then you conclude that there is indeed a cause-and-effect relationship at work.

- **Everything is held constant except one factor which is varied**

- **How many factors are involved when you do an experiment?**

Scientific Method

- How many factors are involved when you do an experiment?

  - Some say two

  → perhaps this is a comparative experiment?

  → Perhaps there is a treatment group and a control group?

  → If you have a treatment group and a control group then in this case you probably only have one factor with two levels.

Game: What are the factors involved to ensure a successful cake?

- **Factors to influence the success**
  - ❑ Preheating the oven
  - ❑ Baking time
  - ❑ Ingredients
  - ❑ Amount of moisture,
  - ❑ Baking temperature, etc.
  - ❑ Mixture...

Game: What are the factors involved to ensure a successful cake?

- To make the recipe a success, we need to make the experiment

  - ❑ What parts of the recipe did they vary to make the recipe a success
  - ❑ Now, should one keep all the factors involved in the experiment at a constant level and just vary one to see what would happen?
  - ❑ This is a strategy that works but is not very efficient.

  → This is one of the concepts that we will address in this course.

Design of Experiments (DOE)

- **All experiments are designed experiments**
  - ❑ **Poorly designed or well-designed**

- **In production and quality control we want to**
  - ❑ **Control the error**
  - ❑ **Learn as much as we can about**
    - ⇨ **the process**
    - ⇨ **the underlying theory with the resources at hand.**

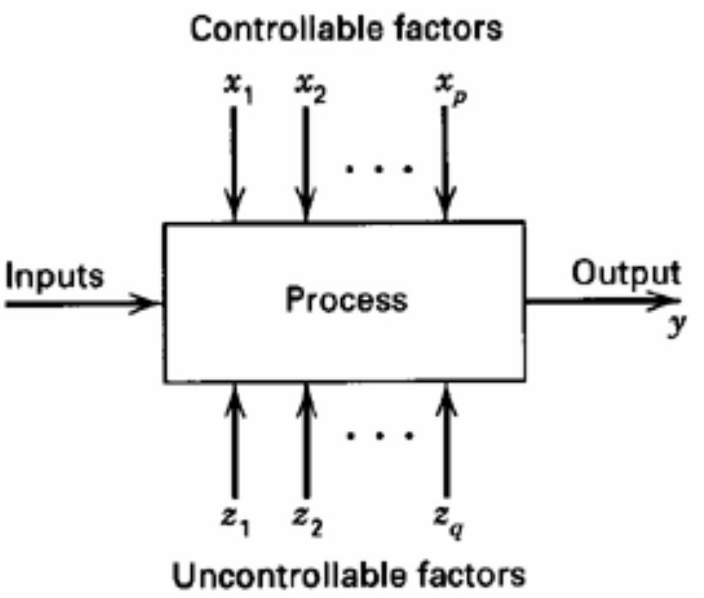
Design of Experiments (DOE)

- Reduce time to design/develop new products & processes
- Improve performance of existing processes
- Improve reliability and performance of products
- Achieve product & process robustness
- Perform evaluation of materials, design alternatives, setting component & system tolerances, etc.

Design of Experiments (DOE)

- **Every experiment design has inputs.**
- **Inputs:**
  - ❑ **iingredients such as flour, sugar, milk, eggs,..**
  - ❑ **Additional factors such as time of baking, temperature, geometry of the cake pan, etc.**

  Some of which you can control and others that you can't control.
- **Output: texture, flavor, height, size, or flavor…**



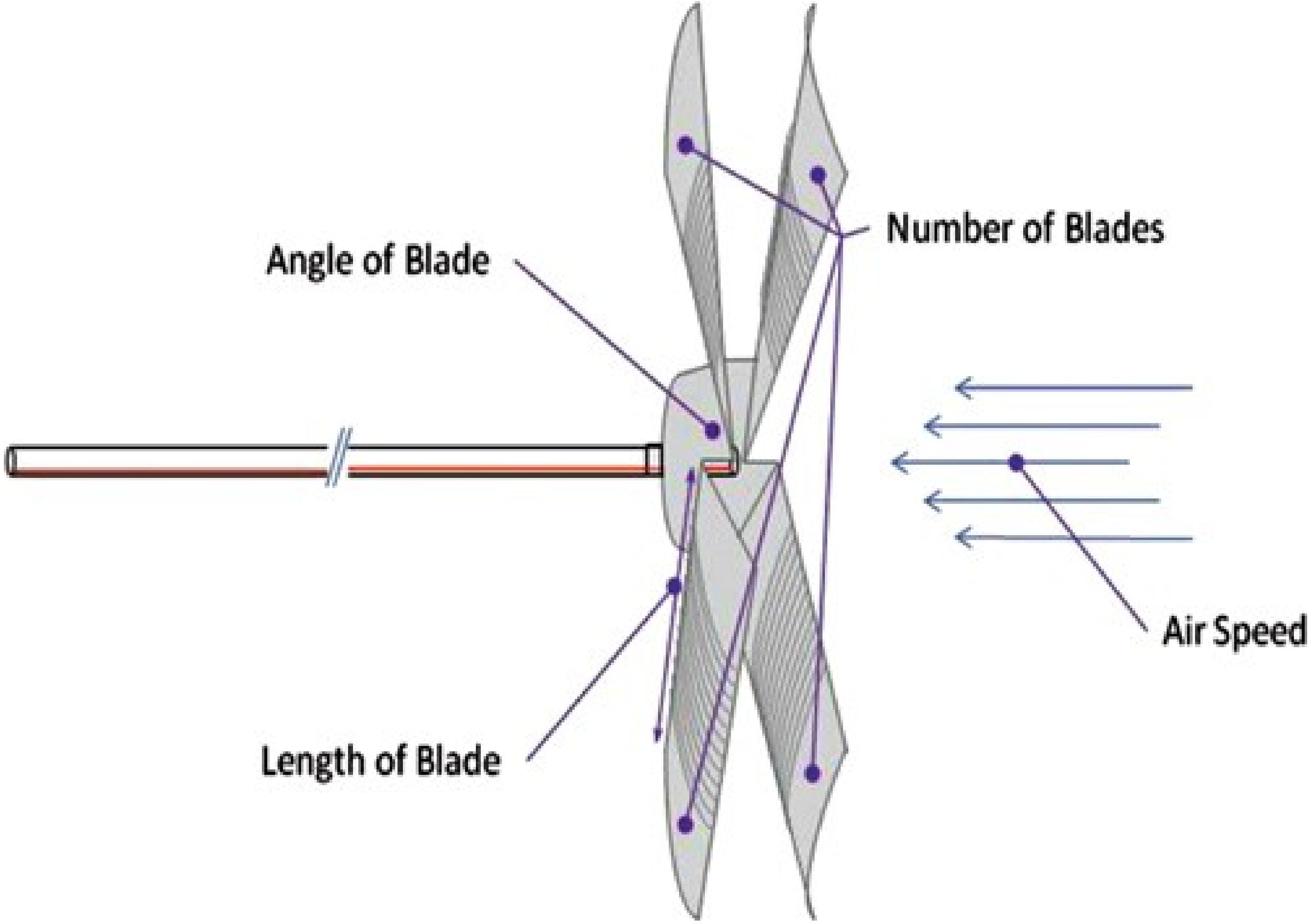
The Basic Principles of DOE

- **Randomization → validity of experiment**
  - **To eliminate potential biases from the conclusions**
  - **In a comparative experiment with two treatments, include in your experimental process the assignment of those treatments by some random process**

- **Replication:**
  - **To estimate or control the uncertainty in our results**
    - ⇨ **achieve this estimate through replication**
  - **To get a handle on how precise our estimates are at the end**
  - **Our estimates of the mean** $\sqrt{\frac{s^2}{n}}$ **become less variable as the sample size *n* increases**

The Basic Principles of DOE

- **Replication:**
  - ❑ **Example: Design of PROPELLERS**



The Basic Principles of DOE

- **Replication:**
  - ❑ **Example: Design of PROPELLERS**

Standard Run order	Design B	Design A	Design L	Design S	First replicate Force	First replicate Rate	Second replicate Force	Second replicate Rate
1	−	−	−	−	3.8	6.0	4.2	6.5
2	+	−	−	−	6.7	10.0	4.6	9.0
3	−	+	−	−	2.6	12.0	2.7	13.5
4	+	+	−	−	4.4	14.5	4.6	14.0
5	−	−	+	−	30.1	7.0	28.7	6.0
6	+	−	+	−	30.2	5.5	26.7	4.5
7	−	+	+	−	27.2	8.5	27.1	8.0
8	+	+	+	−	24.2	7.0	24.2	5.5
9	−	−	−	+	5.6	7.5	2.9	5.5
10	+	−	−	+	8.2	10.0	8.7	11.5
11	−	+	−	+	4.2	14.0	3.9	14.0
12	+	+	−	+	7.2	17.5	6.2	16.5
13	−	−	+	+	39.7	7.0	41.2	7.5
14	+	−	+	+	38.2	5.5	38.7	11.0
15	−	+	+	+	38.2	9.5	37.7	10.0
16	+	+	+	+	33.1	6.0	27.6	7.0

The Basic Principles of DOE

- **Blocking**
  - **A technique to include other factors in your experiment which contribute to undesirable variation.**
  - **to control sources of variation that will reduce error variance**
- **For example: human studies**
  - **gender**
  - **Age**
    - **Age and gender are often considered nuisance factors which contribute to variability and make it difficult to assess systematic effects of a treatment**
    - **Using age and gender as blocking factors, you can avoid biases that might occur due to differences between the allocation of subjects to the treatments, and as a way of accounting for some noise in the experiment.**

The Basic Principles of DOE

- **Multi-factor Designs**
  - ❑ Multi-factor experimental designs: 2^k designs, 3^k designs, response surface designs
  - ❑ Contrary to the scientific method → The one factor at a time method is a very inefficient way of making scientific advances
  - ❑ An experiment that simultaneously includes combinations of multiple factors that may affect the outcome.

The Basic Principles of DOE

- **Cofounding**
  - ❑ **Example 1:**
    - ⇨ **Let's say we are doing a medical study with drugs A and B.**
    - ⇨ **We put 10 subjects on drug A and 10 on drug B.**
    - ⇨ **If we categorize our subjects by gender, how should we allocate our drugs to our subjects?**

The Basic Principles of DOE

- **Cofounding**
  - ❑ **Solutions for Example 1:**
    - ⇨ **Let's make it easy and say that there are 10 male and 10 female subjects.**
    - ⇨ **A balanced way of doing this study would be to put five males on drug A and five males on drug B, five females on drug A and five females on drug B.**
    - ⇨ **This is a perfectly balanced experiment such that if there is a difference between male and female at least it will equally influence the results from drug A and the results from drug B.**

The Basic Principles of DOE

- **Cofounding**
  - **Example 2:**
    - ⇨ **if patients were randomly assigned treatments as they came in the door.**
    - ⇨ **At the end of the study they might realize that drug A had only been given to the male subjects and drug B was only given to the female subjects.**
    - ⇨ **We would call this design totally confounded.**
    - ⇨ **This refers to the fact that if you analyze the difference between the average response of the subjects on A and the average response of the subjects on B, this is exactly the same as the average response on males and the average response on females. You would not have any reliable conclusion from this study at all.**
    - ⇨ **The difference between the two drugs A and B, might just as well be due to the gender of the subjects, since the two factors are totally confounded.**

Steps for Planning, Conducting and Analyzing an Experiment

1. Recognition and statement of the problem
2. Choice of factors, levels, and ranges
3. Selection of the response variable(s)
4. Choice of design
5. Conducting the experiment
6. Statistical analysis
7. Drawing conclusions, and making recommendations

Steps for Planning, Conducting and Analyzing an Experiment

- **Choice of factors, levels, and ranges**

  - ❑ ***Experimental vs. Classification Factors***
    - ⇨ **Experimental Factors**
      - ✓ **these are factors that you can specify (and set the levels) and then assign at random as the treatment to the experimental units.**
      - ✓ **Example: Temperature, level of an additive fertilizer amount per acre**

Steps for Planning, Conducting and Analyzing an Experiment

- **Choice of factors, levels, and ranges**

  - ***Experimental vs. Classification Factors***
    - **Classification Factors**
      - ✓ **can't be changed or assigned, these come as labels on the experimental units.**
      - ✓ **Example:**
        - → **The age and sex of the participants are classification factors which can't be changed or randomly assigned.**
        - → **But you can select individuals from these groups randomly**

Steps for Planning, Conducting and Analyzing an Experiment

- **Choice of factors, levels, and ranges**

  - ***Quantitative vs. Qualitative Factors***
    - ⇨ **Quantitative Factors - you can assign any specified level of a quantitative factor.**
      - ✓ **Examples: percent or pH level of a chemical.**
    - ⇨ **Qualitative Factors - have categories which are different types.**
      - ✓ **Examples: species of a plant or animal, a brand in the marketing field, gender, - these are not ordered or continuous but are arranged perhaps in sets.**

Steps for Planning, Conducting and Analyzing an Experiment

- **Selection of the response variable(s)**

  - **Microwave popcorns:**
    - **Factors: brand, time, power, height (on bottom or raised)**
    - **Responses: taste (maximize), un-popped kernels (minimize)**

  - **Boiling water:**
    - **Factors: pan type, burner size, cover**
    - **Response: time to boil water**

Steps for Planning, Conducting and Analyzing an Experiment

- **Choice of design**

  - **Design of an engineering system (for hydraulics, soil mechanics..)**

    - ⇨ **5 input factors (A, B, C, D, and E)**
    - ⇨ **2 output responses (Y1 and Y2).**

Steps for Planning, Conducting and Analyzing an Experiment

- ## Choice of design

❑ Determine:

- ⇨ The relative contribution of A, B, C, D, and E to the responses Y_1 and Y_2 ;
- ⇨ Which factors have a synergistic or antagonistic effect on the responses;
- ⇨ An equation that can be used to predict Y_1 and Y_2 given values of the input factors; and
- ⇨ What combination of the factors would maximize Y1 but minimize Y2 ?

Steps for Planning, Conducting and Analyzing an Experiment

- **Statistical analysis**
  - ❑ **Example**

TABLE 2 Propeller Experiment Design and Responses for two Replicates (Force in Grams and Rotation Rate in 100s of RPM)

Standard	Design				First replicate		Second replicate	
Run order	B	A	L	S	Force	Rate	Force	Rate
1	−	−	−	−	3.8	6.0	4.2	6.5
2	+	−	−	−	6.7	10.0	4.6	9.0
3	−	+	−	−	2.6	12.0	2.7	13.5
4	+	+	−	−	4.4	14.5	4.6	14.0
5	−	−	+	−	30.1	7.0	28.7	6.0
6	+	−	+	−	30.2	5.5	26.7	4.5
7	−	+	+	−	27.2	8.5	27.1	8.0
8	+	+	+	−	24.2	7.0	24.2	5.5
9	−	−	−	+	5.6	7.5	2.9	5.5
10	+	−	−	+	8.2	10.0	8.7	11.5
11	−	+	−	+	4.2	14.0	3.9	14.0
12	+	+	−	+	7.2	17.5	6.2	16.5
13	−	−	+	+	39.7	7.0	41.2	7.5
14	+	−	+	+	38.2	5.5	38.7	11.0
15	−	+	+	+	38.2	9.5	37.7	10.0
16	+	+	+	+	33.1	6.0	27.6	7.0

Steps for Planning, Conducting and Analyzing an Experiment

- **Statistical analysis**
  - **Example**

TABLE 3 Estimated Coefficients Associated with Factorial Effects Based on First Replicate of Propeller Experiment

Effects	Force	Rate
B	0.05	0.28
A	−1.34	1.91
L	13.64	−2.22
S	2.83	0.41
BA	−0.46	−0.16
BL	−1.24	−1.28
BS	−0.18	−0.16
AL	−0.60	−1.16
AS	0.21	0.29
LS	1.86	−0.41
BAL	−0.38	−0.09
BAS	0.06	0.03
BLS	−0.29	−0.09
ALS	0.08	−0.22
BALS	−0.13	−0.28

Steps for Planning, Conducting and Analyzing an Experiment

- **Statistical analysis**
  - ❑ **Example**

TABLE 4 Analysis of Force and Rotation Rate from Replicated Experiment, Significance Codes, and Associated *p* Values

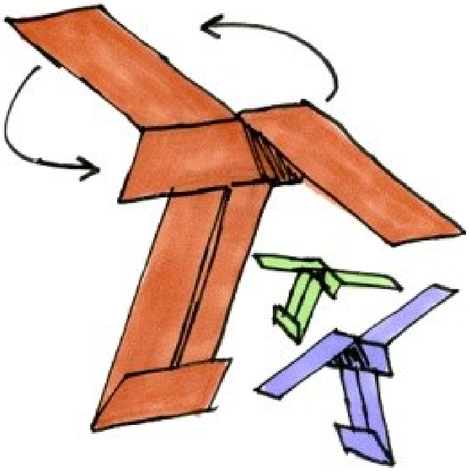
Force	Estimate	Std. error	*t* Value	Pr (>|*t*|)	Significance
Intercept	18.54	0.243	76.30	<2E-16	***
B	−0.20	0.243	−0.81	0.43	
A	−1.35	0.243	−5.54	4.5E-05	***
L	13.51	0.243	55.59	<2E-16	***
S	2.79	0.243	11.48	3.9E-09	***
BA	−0.56	0.243	−2.30	0.04	*
BL	−1.49	0.243	−6.13	1.4E-05	***
BS	−0.15	0.243	−0.60	0.55	
AL	−0.79	0.243	−3.25	0.00	**
AS	−0.22	0.243	−0.91	0.37	
LS	1.96	0.243	8.06	5E-07	***
BAL	−0.39	0.243	−1.61	0.13	
BAS	−0.33	0.243	−1.38	0.19	
BLS	−0.57	0.243	−2.33	0.03	*
ALS	−0.29	0.243	−1.29	0.25	
BALS	−0.12	0.243	−0.48	0.64	

Steps for Planning, Conducting and Analyzing an Experiment

- **Statistical analysis**
  - **Example: Response Function**

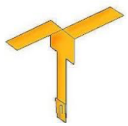
$$\begin{aligned}\hat{y}_{force} = &\ 18.54 - 1.35x_A + 13.51x_L + 2.79x_S \\ &- 0.56x_B x_A - 1.49x_B x_L - 0.79x_A x_L \\ &+ 1.96x_L x_S - 0.57x_B x_L x_S.\end{aligned}$$

Now, let design a paper helicopter



Goal: Making a Better Paper Helicopter

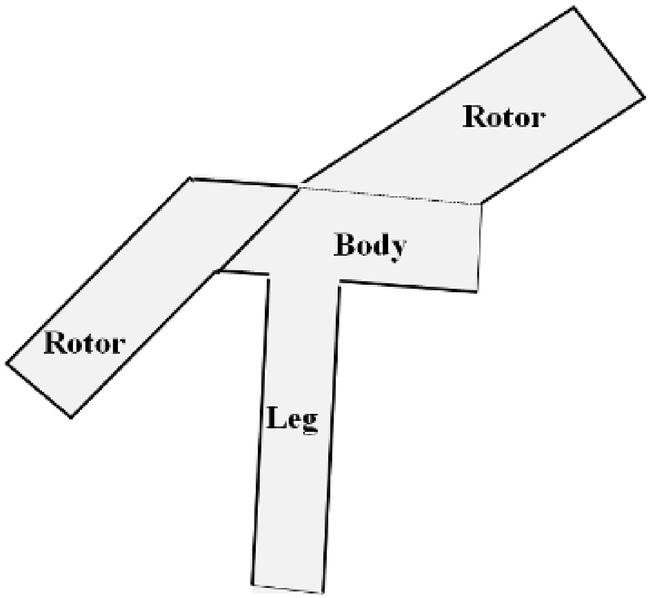
- **Objectives:**
  - ❑ **To increase the flight time: stay in the air for longer time**



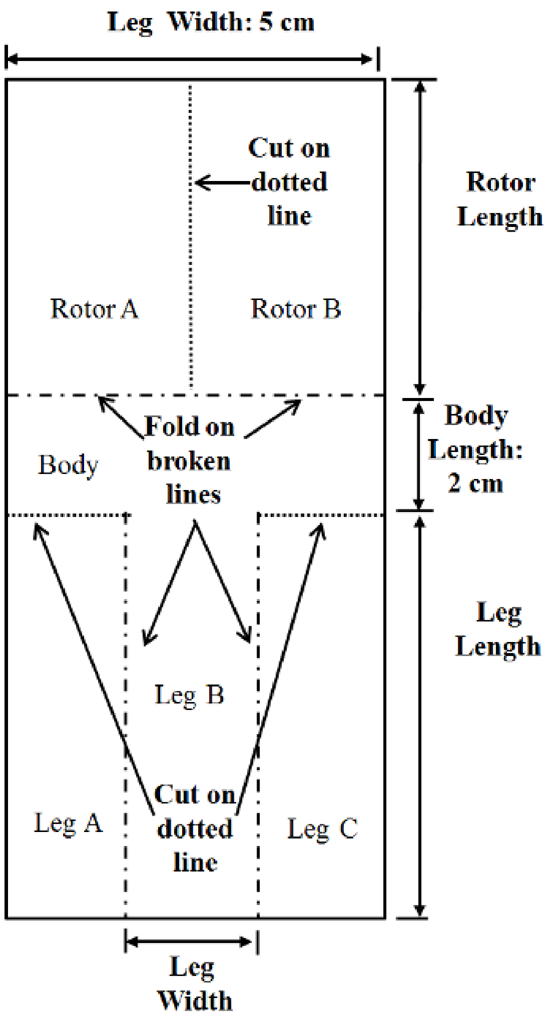
  - ❑ **To analyze the main effects**

Goal: Making a Better Paper Helicopter

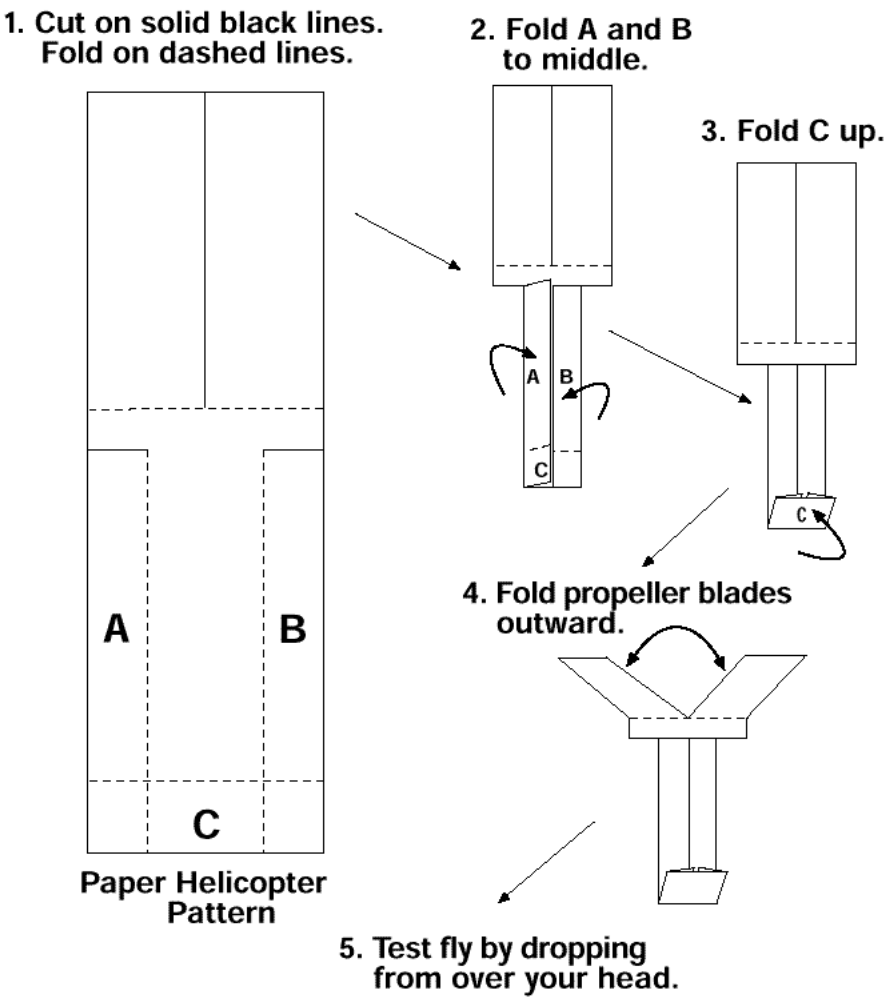
- **Influence factors:**
  - ❑ Paper type
  - ❑ Rotor length
  - ❑ Leg length
  - ❑ Leg width
  - ❑ Number of clips
  - ❑ Wing shapes



Assembly Instruction (1)



Assembly Instruction (2)

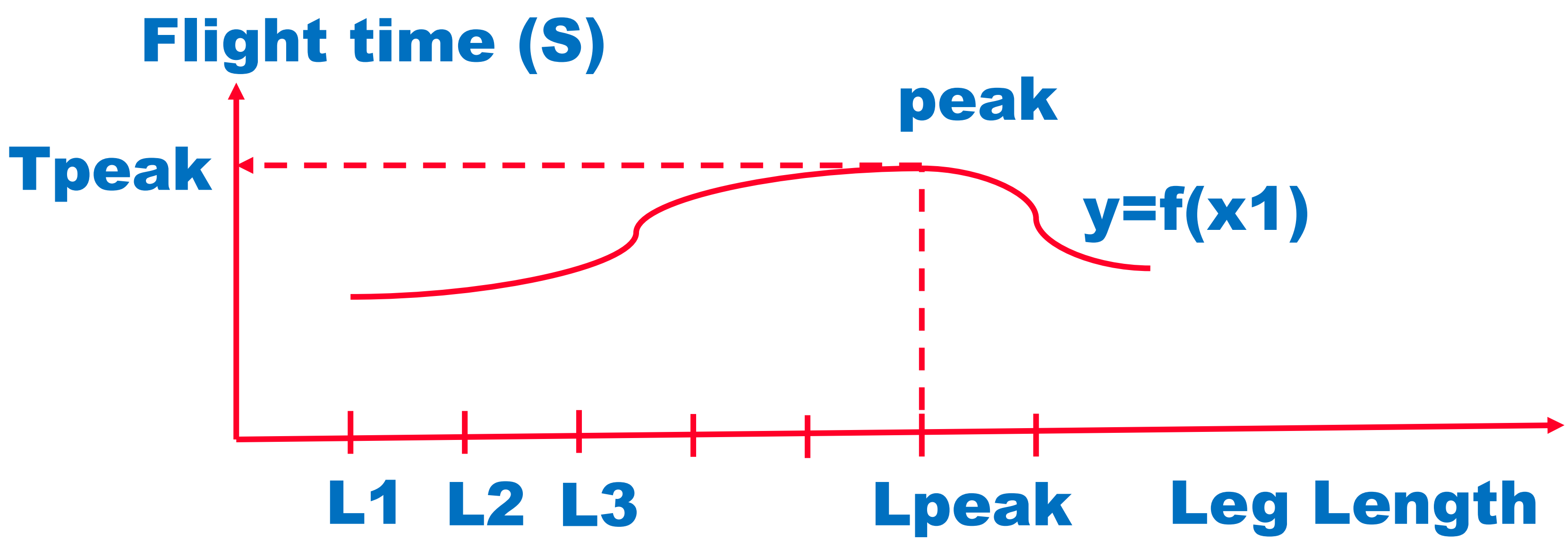


Experiment Results

STT	Rotor Length	Leg Length	Leg Width	Paper Clip On	Flight time (second)
1	R1	L1	W1	Yes	?
2	R1	L2	W1	Yes	?
3	R1	L3	W1	Yes	?
4	....	...	...	...	...
5	R2	Lpeak	W1	Yes	?
6	R3	Lpeak	W1	Yes	?
7	R4	Lpeak	W1	Yes	?
8					
9					
10					

Experiment Results

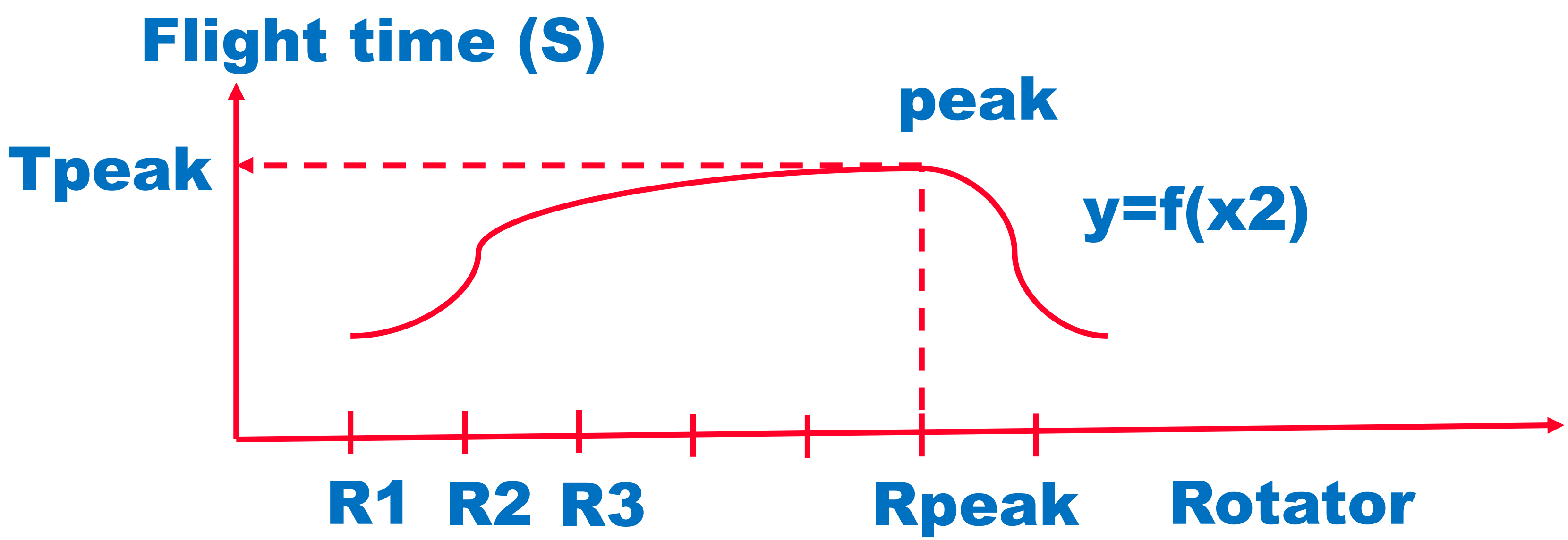
STT	Rotor Length	Leg Length	Leg Width	Paper Clip On	Flight time (second)
1	R1	L1	W1	Yes	?
2	R1	L2	W1	Yes	?
3	R1	L3	W1	Yes	?



Rotor length fixed

Experiment Results

STT	Rotor Length	Leg Length	Leg Width	Paper Clip On	Flight time (second)
5	R2	Lpeak	W1	Yes	?
6	R3	Lpeak	W1	Yes	?
7	R4	Lpeak	W1	Yes	?



Leg Length fixed (Lpeak)

Sample Size Determination

- **Finding the Smallest Sample Size Needed for a Given Margin of Error and Confidence**

  - **want to calculate the smallest sample size**
  -
    - **need to create a 95% confidence interval (CI) with a margin of error (E) of .01.**

Confidence Interval

- **In case the standard deviation is know known σ:**

➢ **Sample Variance :**

❑ $s^2 = \frac{\sum_{i=1}^{n}(xi - X)2}{n-1}$

❑ $\varepsilon = \frac{s}{\sqrt{n}} t_{n-1,1-\frac{\alpha}{2}}$

❑ $t_{n-1,1-\frac{\alpha}{2}}$ **tra bảng:**

[Bảng giá trị phân vị]

Confidence Interval

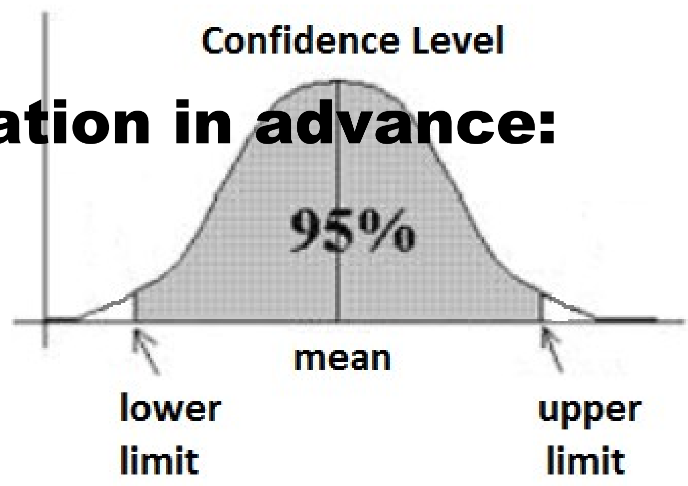
- **Confidence interval a confidence interval (CI) is a type of [interval estimate] (of a [population parameter]) that is computed from the observed data.**
- **Độ tin cậy là xác suất để khi khảo sát một bộ mẫu khác thì trung bình mẫu của bộ đó nằm trong khoảng (lower,upper)**
- ε **là độ chính xác : 2**ε = **upper – lower**

➢ **Công thức xác định:**

- **In case knowing standard deviation in advance:** $\sigma = \sigma_0$**:**

  ❑ $\varepsilon = \frac{\sigma_0}{\sqrt{n}} \cdot Z_{1-\frac{\alpha}{2}}$

  ❑ $Z_{1-\frac{\alpha}{2}}$ **: check the table**



Experiment Results

↓	C1	C2	C3	C4	C5-T	C6	C7	C8	C9-T	C10
	StdOrder	RunOrder	CenterPt	Blocks	Paper type	Rotor length	Leg length	Leg width	Paper clip on	Flight time
1	13	1	1	1	Light	7.5	12.0	5.0	Yes	1.61
2	1	2	1	1	Light	7.5	7.5	3.2	Yes	1.98
3	7	3	1	1	Light	8.5	12.0	3.2	Yes	1.80
4	11	4	1	1	Light	8.5	7.5	5.0	Yes	1.99
5	12	5	1	1	Heavy	8.5	7.5	5.0	No	1.76
6	9	6	1	1	Light	7.5	7.5	5.0	No	2.10
7	5	7	1	1	Light	7.5	12.0	3.2	No	1.56
8	14	8	1	1	Heavy	7.5	12.0	5.0	No	1.54
9	6	9	1	1	Heavy	7.5	12.0	3.2	Yes	1.27
10	15	10	1	1	Light	8.5	12.0	5.0	No	1.87
11	16	11	1	1	Heavy	8.5	12.0	5.0	Yes	1.65
12	2	12	1	1	Heavy	7.5	7.5	3.2	No	1.58
13	10	13	1	1	Heavy	7.5	7.5	5.0	Yes	1.57
14	3	14	1	1	Light	8.5	7.5	3.2	No	2.30
15	4	15	1	1	Heavy	8.5	7.5	3.2	Yes	1.64
16	8	16	1	1	Heavy	8.5	12.0	3.2	No	1.62

❖ **Example:**

- **Consider data in the table: Flight time (t):**
- **Case 1:**
  - $\mu = \frac{\sum_{i=1}^{16} t_i}{16} = 1.74$
  - $\sigma = \text{sqrt}\left(\frac{\sum_{i=1}^{16} (t_i - \mu)^2}{16}\right) = 0.248$
  - **CI = 95% => 1 – α = 0.95 =>**
    Check the Gaussian table at $Z_{1-\frac{\alpha}{2}} = Z_{0,975} = 1.96$
  - **ε = 0,12 s**

❖ Example

- **case 2:**
  - **$s^2 = \frac{\sum_{i=1}^{n}(t_i - \mu)^2}{n-1}$ = 0.065427**
  - **CI = 95% => 1 – α = 0.95 => check the student table: $t_{15\ ;\ 0.975}$ = 2.131**
  - **Require ε = 0.05 => n = 118**