DESIGN OF EXPERIMENTS: IMPROVING FLIGHT TIME OF A PAPER HELICOPTER

ISEN 616 – Design of Experiments

A Report

by

Jeet Mehta (827007434)
Saurabh Jain (527002462)
Yash Mehta (228002156)

April 2020

Major Subject: Industrial Engineering

Contents

EXECUTIVE SUMMARY

The following is a project report to design and improve the flight time of a paper helicopter using the design and analysis of experiments methodologies so that it can fly the longest possible. Our goal is to see how much the flight time for a Marine Zero paper helicopter can be improved.

We first selected the factors which we need to include in our model and brainstormed for reasonable values of low-level and high-level limits for these factors. We then created several samples of helicopters with these different dimensions to collect response data in form of Flight time using a stopwatch. Using Minitab, we decided to apply DOE on a 2-level 8-run fractional factorial design with resolution III and 5 factors. The design constraints specified in the project description were also considered while devising these experiments.

A linear regression model was created using the fractional factorial design and significant factors along with their coefficients were calculated using Pareto charts, ANOVA tables and Half-Normal plots. To cross-check the important factors, we also used main effect and interaction effect plots and it led to similar results. A maximum flight time of 2.377 secs was obtained by employing optimal dimensions of the paper helicopter.

We believe this response value can be further improved by adding non-linear factors to the model and also by creating a greater number of experiments and using a full factorial design to avoid missing any combination of factors, though this can increase the computational cost and time significantly.

INTRODUCTION

To perform a DOE on a paper helicopter, we first need to identify our response (the desired output). We cannot just define our objective as to achieve a high-quality helicopter. We need a tangible response variable that can prove the design is optimal.

The purpose of this project given in the description is to improve the design of paper helicopter so that it can fly the longest possible. Thus, we can have 'Flight Time' as our response variable where we can decide the optimal design of the helicopter with dimensions such that it stays in the air for a longer time. We define this response variable to be the flight time as measured from the time the helicopter is dropped from a pre-determined height (80 inches) from the ground until the time it hits the floor. Our DOE results would be invalid if the testing conditions are not properly defined. It could be possible that the sample helicopter is dropped from different heights by different person for every replication. We make sure that this height is fixed for all our experiments and response time is calculated by the same person to reduce the variance in noise.

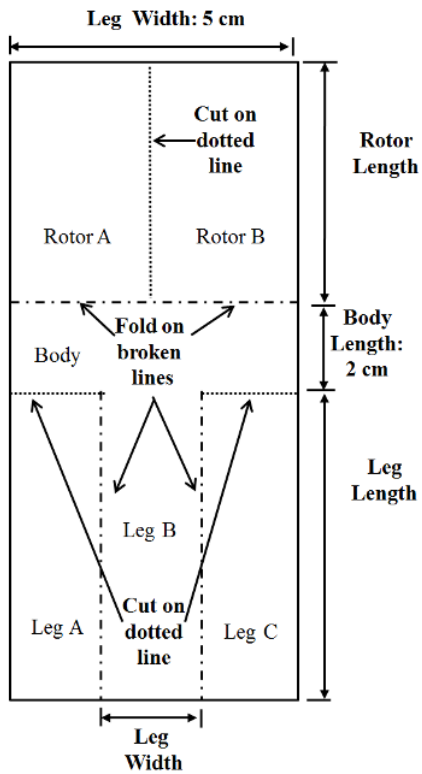
Next, we must also identify the test factors that influence flight time. Some of the factors given in the project description are-

1) Wing length
2) Wing width
3) Body length
4) Body width
5) Middle body length

Other factors which might impact flight time include paper type, overall weight, room conditions (indoor/outdoor), use of paper clips, cello tapes, etc. But for this project, we decide to use the same 5 factors as given in the project description and will not be considering the other factors.

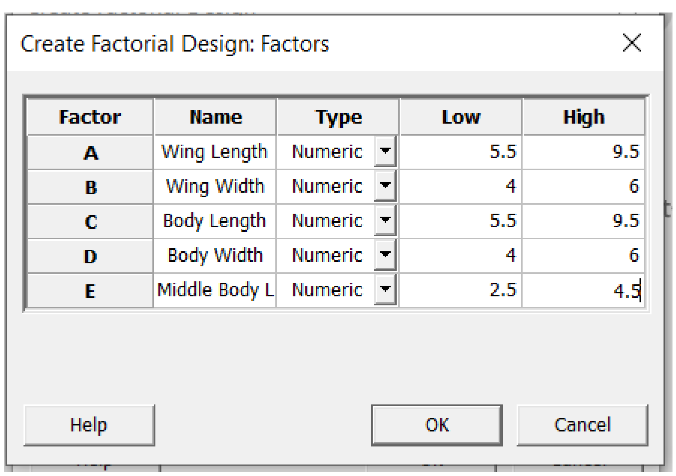
DATA COLLECTION

We create an initial design of the sample paper helicopter as shown in the figure-



Helicopter plan

We create a 2-level 5-factor quantitative design with the following helicopter dimensions-



Factor	Name	Type	Low	High
A	Wing Length	Numeric	5.5	9.5
B	Wing Width	Numeric	4	6
C	Body Length	Numeric	5.5	9.5
D	Body Width	Numeric	4	6
E	Middle Body L	Numeric	2.5	4.5

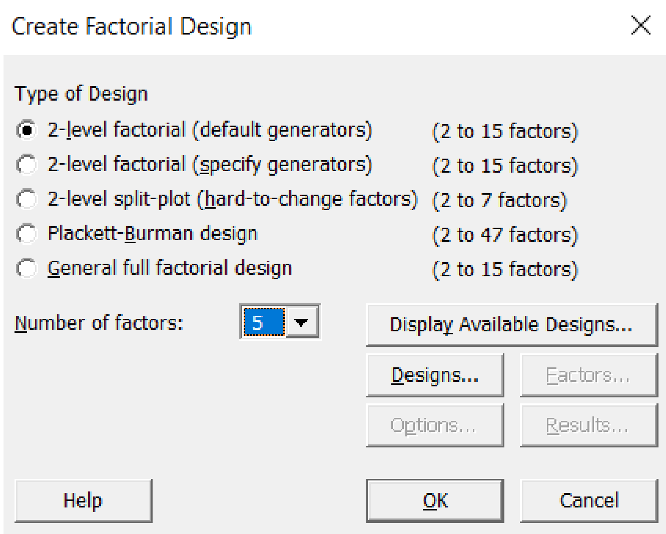
Helicopter factors

After creating various combinations of helicopters, we calculate the flight time for 8 runs with 5 replications each and create a Design Planning matrix for these 40 experiments. Below table shows flight time response calculations for 5 replications (best 5 trials of the 7 repeated experiments) for 8 random runs and its average response time used to design and analyze the model-

Runs	Flight Time (in secs) for 5 replications					Average response time
1	1.77	1.80	1.92	1.94	1.68	1.822
2	2.46	2.54	2.18	2.44	2.47	2.418
3	1.75	1.77	1.67	1.86	1.75	1.760
4	1.81	1.80	1.90	1.77	2.11	1.878
5	1.63	1.64	2.03	1.91	1.82	1.806
6	1.51	2.20	2.28	1.53	2.25	1.954
7	1.37	1.41	1.49	1.47	1.41	1.430
8	1.73	1.70	1.53	1.94	1.98	1.776

DESIGNING THE EXPERIMENT

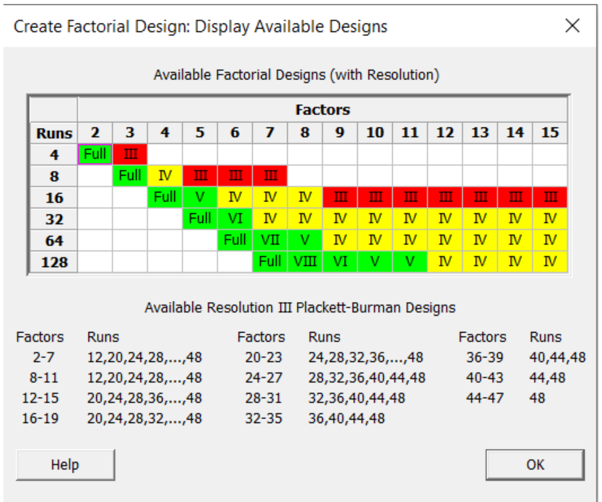
For this experiment, we will use a 2-level factorial design with 5 factors.



Available options for resolution of factorial designs can be checked using Minitab. We see that for a 5-factor design, we have these 3 options-

1) 8-run fractional factorial design with resolution III
2) 16-run fractional factorial design with resolution V
3) 32-run full factorial design

NOTE: We will only consider a linear model for the initial design of this project. It is possible to improve the design by using non-linear quadratic elements in the model; create star points, center-points and perform Canonical analysis.



Create Factorial Design: Display Available Designs

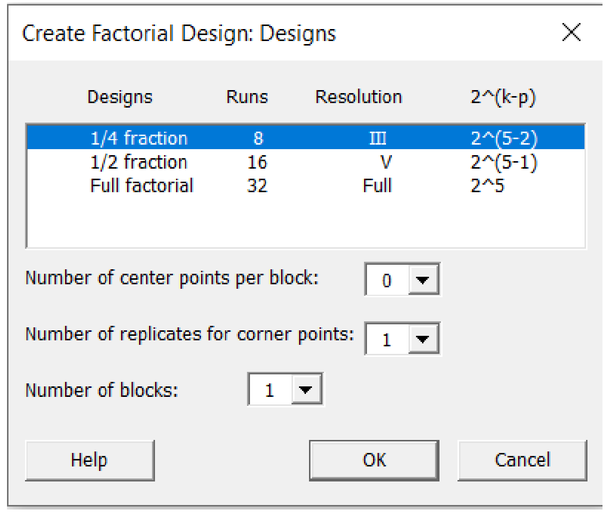
Available Factorial Designs (with Resolution)

Runs	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Available Resolution III Plackett-Burman Designs

Factors	Runs	Factors	Runs	Factors	Runs
2-7	12,20,24,28,...,48	20-23	24,28,32,36,...,48	36-39	40,44,48
8-11	12,20,24,28,...,48	24-27	28,32,36,40,44,48	40-43	44,48
12-15	20,24,28,36,...,48	28-31	32,36,40,44,48	44-47	48
16-19	20,24,28,32,...,48	32-35	36,40,44,48		

Help OK



Create Factorial Design: Designs

Designs	Runs	Resolution	2^(k-p)
1/4 fraction	8	III	2^(5-2)
1/2 fraction	16	V	2^(5-1)
Full factorial	32	Full	2^5

Number of center points per block: 0

Number of replicates for corner points: 1

Number of blocks: 1

Help OK Cancel

The resolution of a design is the smallest word length of the defining words associated with this design. It benchmarks the capability in estimating the factorial effects of a fractional factorial design.

A disadvantage of a fractional factorial design is that every possible combination of factors is not tested separately. However, not testing every possible combination can be a significant advantage in time and expense over a full factorial design. As a result, we select the first option of 8-run fractional factorial design with resolution III with no center points. Also, the number of blocks (homogenous groupings of measurements that can be used to account for variation) are set to 1 by default.

Fractional Factorial Design

Design Summary

Factors:	5	Base Design:	5, 8	Resolution:	III
Runs:	40	Replicates:	5	Fraction:	1/4
Blocks:	1	Center pts (total):	0		

*** NOTE * Some main effects are confounded with two-way interactions.**

Design Generators: D = AB, E = AC

Alias Structure

I + ABD + ACE + BCDE
A + BD + CE + ABCDE
B + AD + CDE + ABCE
C + AE + BDE + ABCD
D + AB + BCE + ACDE
E + AC + BCD + ABDE
BC + DE + ABE + ACD
BE + CD + ABC + ADE

GATHERING EXPERIMENTAL DATA

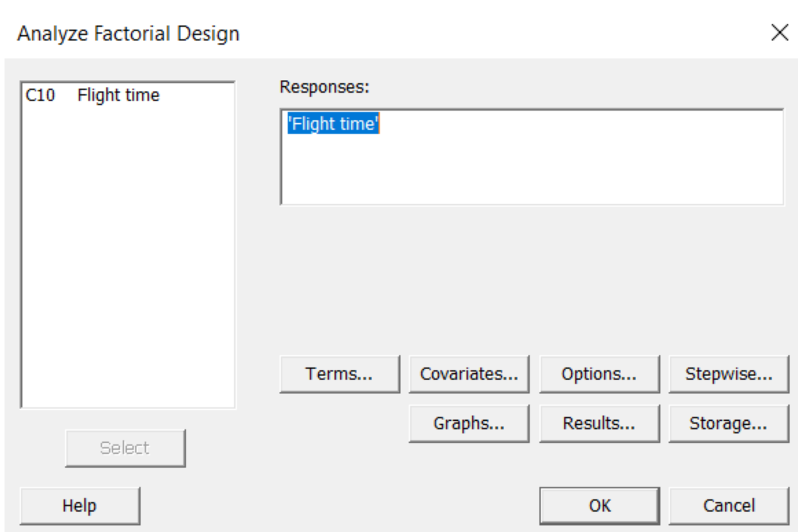
The below figure shows a design planning matrix for the first 10 Experiments with average flight times in Minitab-

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	StdOrder	RunOrder	CenterPt	Blocks	Wing Length	Wing Width	Body Length	Body Width	Middle Body Length	Flight time
1	1	33	1	1	5.5	4	5.5	6	4.5	1.94
2	2	22	1	1	9.5	4	5.5	4	2.5	2.46
3	3	21	1	1	5.5	6	5.5	4	4.5	1.75
4	4	10	1	1	9.5	6	5.5	6	2.5	1.81
5	5	34	1	1	5.5	4	9.5	6	2.5	1.63
6	6	17	1	1	9.5	4	9.5	4	4.5	1.51
7	7	35	1	1	5.5	6	9.5	4	2.5	1.37
8	8	32	1	1	9.5	6	9.5	6	4.5	1.73
9	9	20	1	1	5.5	4	5.5	6	4.5	1.80
10	10	25	1	1	9.5	4	5.5	4	2.5	2.54

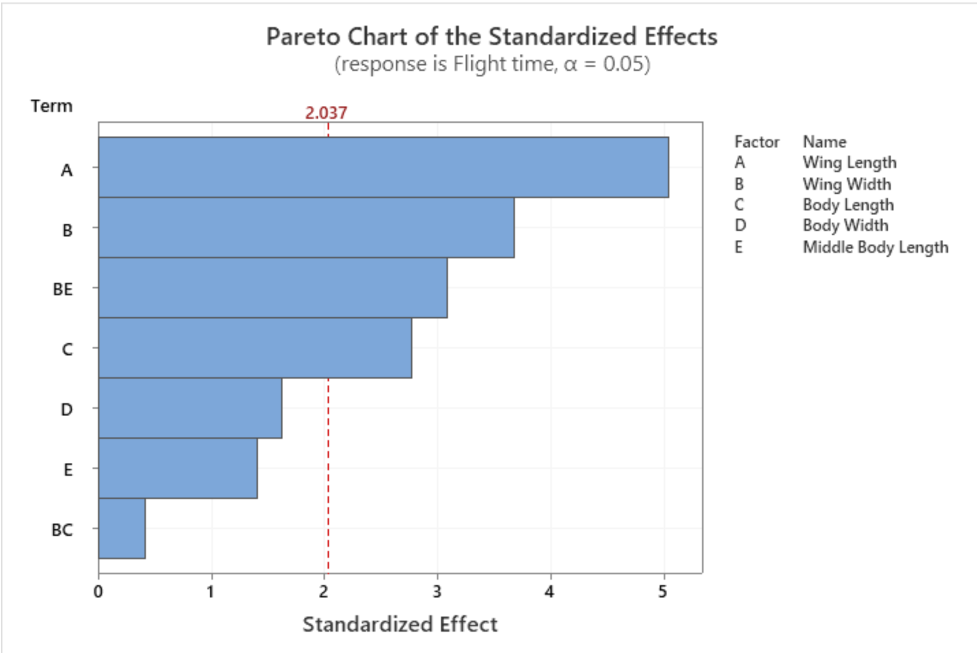
The order in which certain experimental settings are applied in performing the experiment, and the order in which the responses are measured, should be randomized. Otherwise, it may generate an unwanted systemic effect in the data that will distort our understanding of the process. A randomized run order is provided in the “RunOrder” column.

ANALYSING THE DATA

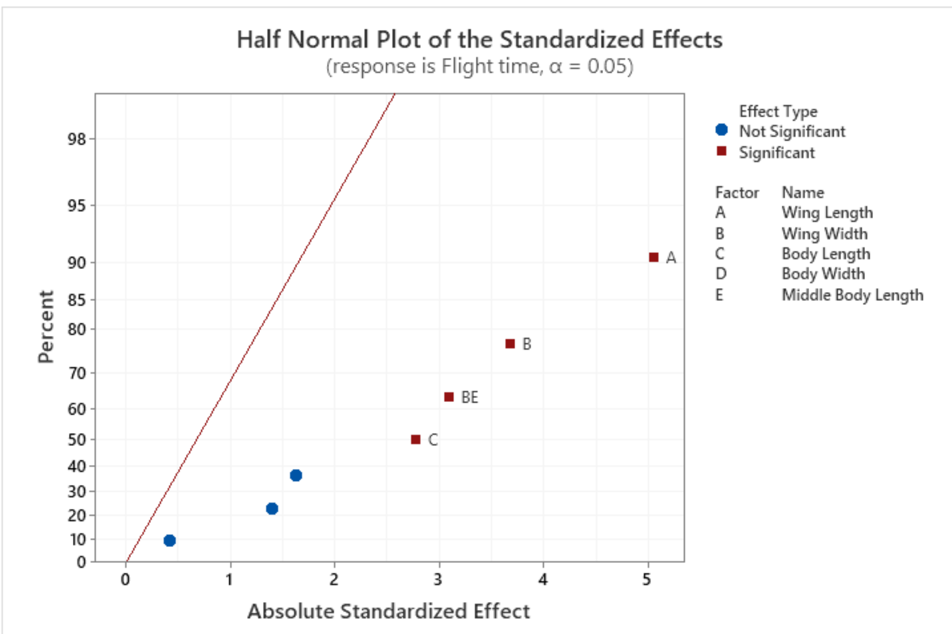
We analyze the fractional factorial design with ‘Flight Time’ as the response-



Minitab provides a list of significant factors that influence the flight time in the form of a Pareto chart and ANOVA table. The Pareto chart of standardized effects shows that the main significant factors are Wing length *(l)*, Wing width *(w)* and Body length *(L)*. The interaction between Middle body length *(d)* and Wing width *(w)* also plays a significant role in influencing the response.



The same conclusion can be drawn from a Half-Normal plot for these variables-



Our intention is to choose an appropriate model to represent the system response. Toward that goal, our job is to determine which model parameters in the β vector should be kept because the observations demonstrate its significance and which parameters in the β vector should be discarded because it is shown insignificant. ANOVA analysis helps us with determining the significant factors which again yields the same conclusion as the Pareto chart and Half normal plot. The factors and interactions with p-value less than 0.05 are considered significant. Also, we get a linear regression model with all factors and their coefficients.

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		1.8355	0.0339	54.14	0.000	
Wing Length	0.3420	0.1710	0.0339	5.04	0.000	1.00
Wing Width	-0.2490	-0.1245	0.0339	-3.67	0.001	1.00
Body Length	-0.1880	-0.0940	0.0339	-2.77	0.009	1.00
Body Width	-0.1100	-0.0550	0.0339	-1.62	0.115	1.00
Middle Body Length	-0.0950	-0.0475	0.0339	-1.40	0.171	1.00
Wing Width*Body Length	-0.0280	-0.0140	0.0339	-0.41	0.682	1.00
Wing Width*Middle Body Length	0.2090	0.1045	0.0339	3.08	0.004	1.00

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	2.79899	0.39986	8.70	0.000
Linear	5	2.35434	0.47087	10.24	0.000
Wing Length	1	1.16964	1.16964	25.44	0.000
Wing Width	1	0.62001	0.62001	13.49	0.001
Body Length	1	0.35344	0.35344	7.69	0.009
Body Width	1	0.12100	0.12100	2.63	0.115
Middle Body Length	1	0.09025	0.09025	1.96	0.171
2-Way Interactions	2	0.44465	0.22232	4.84	0.015
Wing Width*Body Length	1	0.00784	0.00784	0.17	0.682
Wing Width*Middle Body Length	1	0.43681	0.43681	9.50	0.004
Error	32	1.47120	0.04597		
Total	39	4.27019			

Regression Equation in Uncoded Units

Flight time = 4.177 + 0.0855 Wing Length - 0.438 Wing Width - 0.0120 Body Length
- 0.0550 Body Width - 0.570 Middle Body Length - 0.0070 Wing Width*Body Length
+ 0.1045 Wing Width*Middle Body Length

We rerun the analysis to eliminate some factors until only significant factors and their interactions remain. A stepwise regression feature is used to reduce this model further. The factors and interactions with p-value less than 0.05 are considered significant. Hence, the alpha to remove using the backward elimination Technique is also 0.05. Also, we get a linear regression model with all factors and their coefficients.

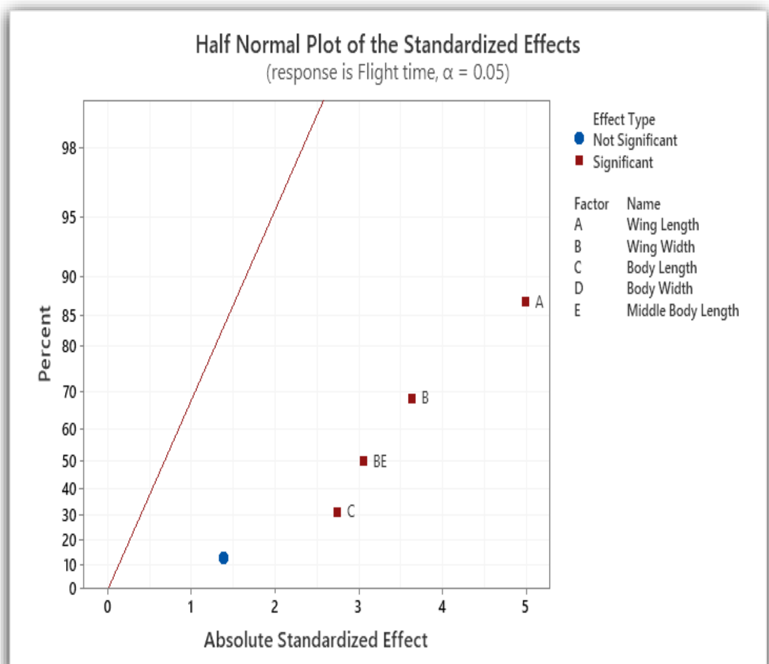
The ANOVA & Half-Normal Plot of the Model with significant effects:

Analysis of Variance

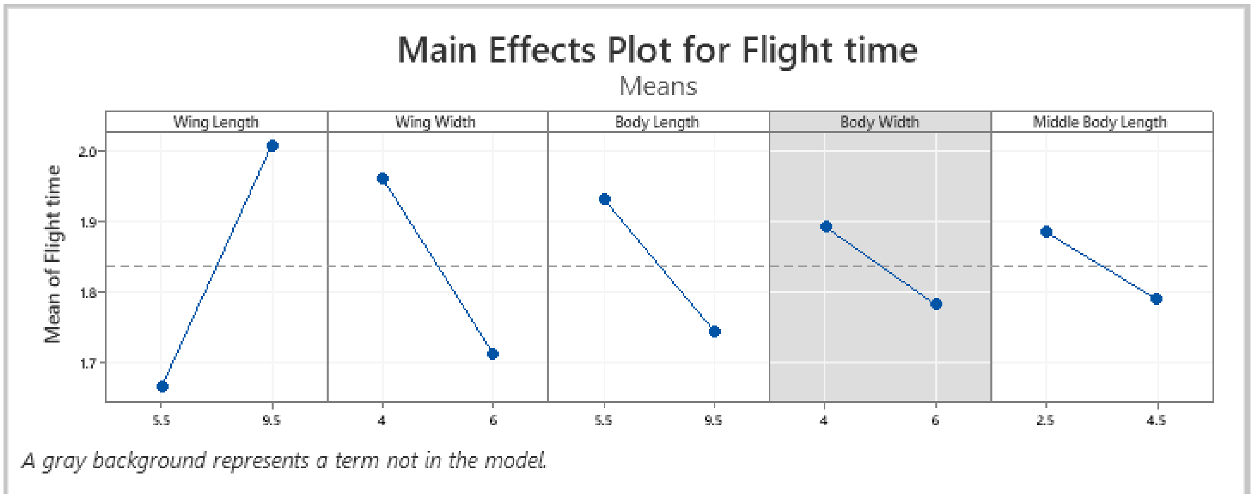
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	2.67015	0.53403	11.35	0.000
Linear	4	2.23334	0.55834	11.86	0.000
Wing Length	1	1.16964	1.16964	24.85	0.000
Wing Width	1	0.62001	0.62001	13.17	0.001
Body Length	1	0.35344	0.35344	7.51	0.010
Middle Body Length	1	0.09025	0.09025	1.92	0.175
2-Way Interactions	1	0.43681	0.43681	9.28	0.004
Wing Width*Middle Body Length	1	0.43681	0.43681	9.28	0.004
Error	34	1.60004	0.04706		
Lack-of-Fit	2	0.12884	0.06442	1.40	0.261
Pure Error	32	1.47120	0.04597		
Total	39	4.27019			

Regression Equation in Uncoded Units

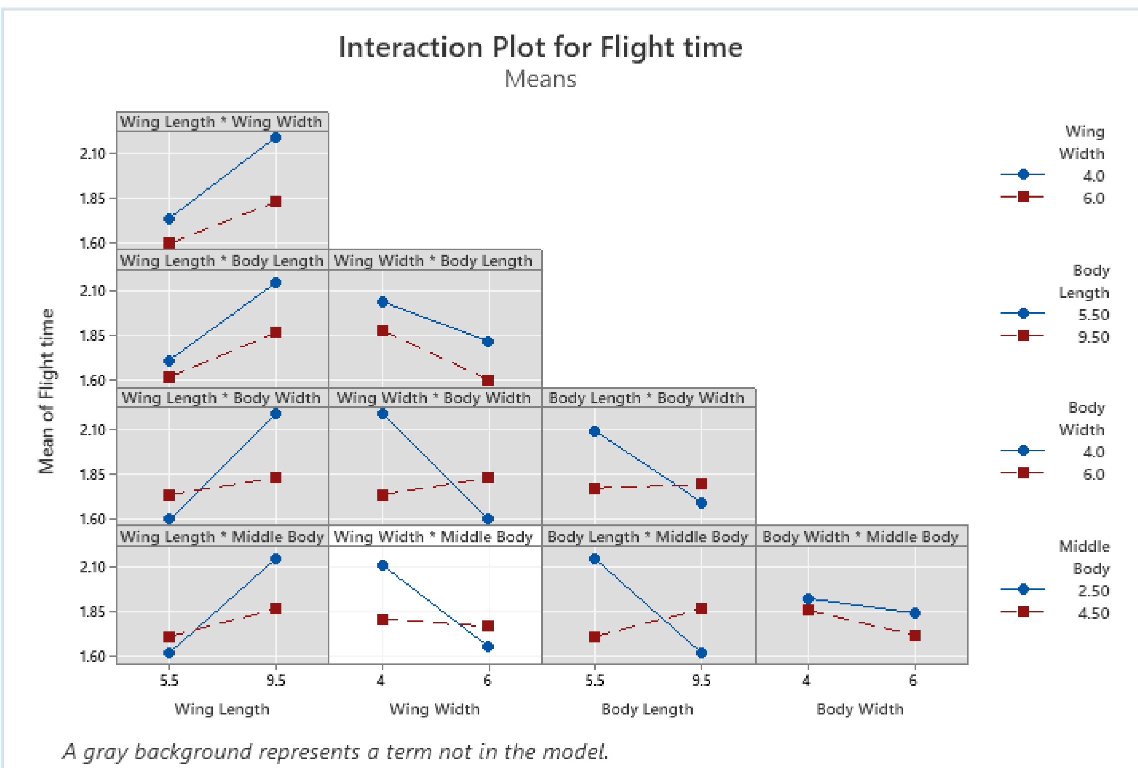
Flight time = 4.164 + 0.0855 Wing Length - 0.490 Wing Width - 0.0470 Body Length - 0.570 Middle Body Length + 0.1045 Wing Width*Middle Body Length



We plot the main effect plots and interaction effect plots for flight time with all factors-



Since this is a larger-the-better type of problem, we select those level values which result in a higher mean flight time.



We fix the wing width to be 4 cm from the Main Effects plot. From the interaction plots, we can improve the flight time by using middle body length as 2.5 cm which leads to the same conclusion as its main effect plot.

The optimal values for all main effects and its corresponding flight time (after substituting all values in the linear regression model) is found to be as follows-

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Flight time	Maximum	1.12	2.54		1	1

Solution

Solution	Wing Length	Wing Width	Body Length	Middle Body Length	Flight time Fit	Composite Desirability
1	9.5	4	5.5	2.5	2.377	0.885211

Response	Fit	SE Fit	95% CI	95% PI
Flight time	2.3770	0.0840	(2.2063, 2.5477)	(1.9042, 2.8498)

CONCLUSION

Design of experiment is considered to be one of the most powerful tools in finding optimum conditions for any experiment and with great capability in improving the performance of experiments. The experiment was conducted to optimize the paper helicopter flight time by considering a minimum number of trials. For the data we collected, our analysis with Minitab indicates the optimal helicopter settings are-

Wing length = 9.5 cm

Wing width = 4 cm

Body Length = 5.5 cm

Middle body length = 2.5 cm

Response = Flight time = 2.377 secs

FUTURE RECOMMENDATIONS

To design an even better helicopter, we could repeat the entire DoE using other factors such as different types of paper and use of paper clips and cello tapes. The design can also be improved by adding non-linear elements in the model and creating center-points, star-points and performing Canonical analysis to simplify the model so that the optimal setting and response can be determined easily and calculate higher order effects and their interactions.

REFERENCES

https://www.minitab.com/en-us/Published-Articles/Teaching-DoE-with-Paper-Helicopters-and-Minitab/

G.E.P. Box, “Teaching Engineers experimental design with a paper helicopter”. Report no. 76, Center for Quality and Productivity Improvement, University of Wisconsin, (1991).

Siorek, T., & Haftka, R. (1998). Paper helicopter-experimental optimum engineering design classroom problem. In *7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization* (p. 4963).