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A study about how to use experimental design to increase the efficiency in a research project

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Abstract. In the design of a product, creating a model generally involves establishing a number of physical quantities which are allowed to be modified. Therefore experimental studies are needed to impose different values of these parameters and to measure the responses obtained. The experimental design consists of selecting and ordering the tests as to identify, at lower costs, the effects of the parameters on the response of the product. To perform an experimental design with a paper helicopter it is mandatory to identify the desired output, which would be the response variable. A good helicopter is one which stays in the air for a longer time, so the response variable would be flight time. The experiment input data are varied by using different types of paper weight, longer or shorter leg and rotor lengths, and adding or removing paper clips. In this paper two approaches were made: one with the full factorial plan, in which we considered that the factors had only two levels and the second with the fractional factorial plan using the Taguchi tables. At the end of the experimental design, a model of the global behavior is available, which can be used to carry out simulations.

1. Introduction

When there is a dispersal or instability in the characteristics of a product when manufactured or used, the causes are sought to reduce or even eliminate them. However, these causes may be multiple: the variability of environmental conditions (temperature, humidity, dust, etc.), the variability of the characteristics of the raw materials and the components used, the different operating modes of the workers. Means commonly used to combat them can sometimes cost very much: reducing the tolerance range for used materials, oversize components, more or less sophisticated devices for conditioning workshops, overly rigid rules of use or product operation.

The strategy adopted by Genichi Taguchi is diametrically opposed: instead of seeking to eliminate these noise factors, he sought to minimize their impact [1].

Specifically, it consists in identifying combinations of parameters that reduce the effects of the causes without directly attacking them. Parameters about the product or its manufacturing process, on which we can easily act, are called controlled factors. The search for good values to be attributed to controlled factors is done experimentally in order to optimize the product or process so that it can:
- observe the desired functional performance;
- be robust, that is insensitive to noise factors and with the lowest possible cost.

Attempts to develop a product or process are an integral part of engineer's work. They are determined to investigate the values of the parameters defining the products or the parameters of production means adjustment in order to achieve the desired performances. The logical step is to try

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one parameter at a time. Each new test follows from the observations made on this occasion or the previous attempts. But, one cannot say beforehand how many attempts will be needed, or whether they will be successful. It is possible to get faster and cheaper results, relying on experimental design.

2. Different experimentation methods

The purpose of an experiment is, for example, to find out what is the best material, the best working temperature, the best time of the cycle, etc., which, introduced in the manufacturing process, determines the best desired results, in the most reliable and economical conditions possible [2].

There are three methods of experimentation:
- experiments carried out varying only one factor at a time;
- experiments with a full factorial plan;
- experiments with a fractional factorial plan.

2.1. Experiments carried out varying only one factor at a time

It is the method that is used spontaneously in a more or less intuitive manner. Generally, it is done through successive drills, often conducted without a specific methodology, i.e. without a clearly predetermined experimental plan. A new factor, or a new value of that factor, is attempted, depending on the results obtained during the previous test.

At first glance, this approach seems indeed objective. However, it must be abandoned because it is not realistic. In fact, each level of each factor is attempted only in relation to a single configuration of the levels of the other factors. This would not be a major inconvenience if the effects would always be independent of each other, and if there were never any parasitic influences. But this is not the case [3].

2.2. Experimenting with a full factorial plan

A full factorial plan studies all the possible combinations of the levels of factors tested. The deficiencies previously reported to the experimental method, which vary by only one factor at a time, are totally eliminated.

For example, the complete factorial plan with 7 factors at two levels requires $2^7 = 128$ tests.

With this type of plan, it can be seen that the number of trials follows a geometric progression depending on the increasing number of factors. For example, with one more factor (to be 8 in total) means that $2^8 = 256$ attempts are required.

With the 7 initial factors, but at 3 levels instead of 2, a complete factorial plan requires $3^7 = 2187$ attempts.

In the issue of product optimization or manufacturing processes, 15 factors are often attempted at 2 levels. Then there should be $2^{15} = 32{,}768$ attempts, which is actually unrealistic!

Factoring experience plans are theoretically complete, but experimental deadlines and costs become prohibitive as soon as 3 or 4 factors are exceeded.

2.3. Experimenting with a fractional factorial plan

A fractional factorial orthogonal plane allows us to obtain (almost) the same effective information we obtain with a fully equivalent factorial plan, greatly reducing the number of attempts being made [4].

The orthogonality of a fractional factorial plan is a feature that allows isolation of the individual effects of different factors tested in multimodal conditions.

3. Objective

To perform an experimental design with a paper helicopter it is mandatory to identify the desired output, which would be the response variable [5].

A good helicopter is one which stays in the air for a longer time, so the response variable would be flight time as measured from the time the helicopter is dropped from a height of six meters until the time it hits the floor. Without defining the test conditions it could be possible that sample helicopters would be dropped from different heights, in which case our experimental results would not be valid.

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Test factors that influence the flight time must also be identified. For this experiment the factors are: paper type, rotor length, leg length, leg width and paper clip position. The helicopter experiment levels are varied by using two different types of paper weight, longer or shorter leg and rotor lengths, and adding or removing a paper clip.

4. Methodology

To make a paper helicopter we have to follow these steps:

1. Cut the paper on the outer contour, as seen in figure 1.
2. Cut the paper on the broken line.
3. Fold left wing and right wing in opposite directions. They should form 90° to the body and be 180° away from each other.
4. For the paper clip version add a paper clip to the bottom of the leg as shown in figure 2.

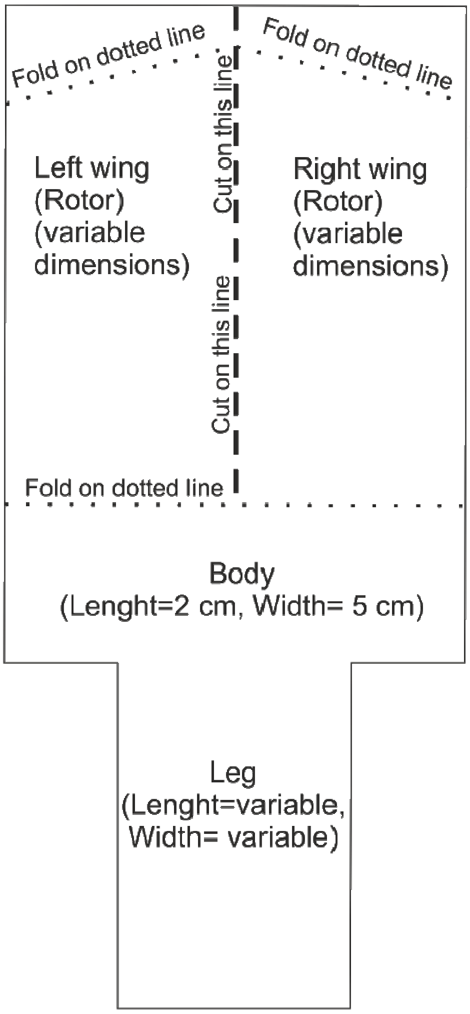

Figure 1. The helicopter drawn on paper.

Figure 2. The finished helicopter.

A large number of factors that might affect the flight time are proposed during a brainstorming session, and the list is finally limited to five factors which are to be studied through a factorial experiment. The five factors and their respected levels are listed in table 1.

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Table 1. Factors and levels suggested.

Factor	Low setting (-)	High setting (+)
Paper type	Light	Heavy
Rotor length	7.5 cm	8.5 cm
Leg length	7.5 cm	12.0 cm
Leg width	3.2 cm	5.0 cm
Paper clip on leg	No	Yes

Paper type determines aerodynamic properties of the helicopter: its weight, elasticity, coefficients of friction and balance. Paper type also determines appearance and durability of the vehicle.

Wing length (or rotor blade length) is one of the main parameters of the paper helicopter. Short blades reduce drag and give higher rotation speeds (also increasing balance and stability of the flight), while large wings suit best for heavy lifting and slow glide. We have to understand that:

- Body length determines the center of mass position of the paper helicopter.
- Body width determines load capacity of the paper helicopter.
- Paper clips are important for the balance of the paper helicopter.
- Paper clips (at least one) must be attached to the end of the paper helicopter body according to the marking.

In order to design the experiment we use Minitab statistical software [6] which makes this task easier. For this experiment, we will use a 2 level factorial which can handle five different factors.

We have to decide which resolution to use in the program. Resolution is defined by the degree to which effects are aliased with other effects. In short, aliased effects are mixed and can not be estimated separately. This can also be referred to as confounding, and it results from not testing every possible combination of factors. This is a disadvantage of a fractional factorial design, but by not testing every possible combination can be an important advantage in time and cost over a full factorial design. In the quality domain, we typically use three levels of resolution: resolution III, IV and V. There is no confounding of main effects with each other in these three resolution types.

Observing the available designs in Minitab, we can perform a fractional factorial experiment using either a resolution III or a resolution V design. A resolution III would need only 8 runs, but the resolution V which requires 16 test runs is the better option.

After we select the design, we enter the names and levels of the variables in our experiment. When we've completed the dialog box, Minitab creates the experimental design and displays it in a Minitab worksheet, as in table 2.

Table 2. Design Minitab worksheet (first half) with the variables.

	StdOrder	RunOrder	CenterPt	Blocks	Paper type	Rotor length (cm)	Leg length (cm)	Leg width (cm)	Paper clip on
1	2	1	1	1	Heavy	7,5	7,5	3,2	No
2	12	2	1	1	Heavy	8,5	7,5	5,0	No
3	5	3	1	1	Light	7,5	12,0	3,2	No
4	15	4	1	1	Light	8,5	12,0	5,0	No
5	13	5	1	1	Light	7,5	12,0	5,0	Yes
6	16	6	1	1	Heavy	8,5	12,0	5,0	Yes
7	1	7	1	1	Light	7,5	7,5	3,2	Yes
8	7	8	1	1	Light	8,5	12,0	3,2	Yes

Variability can have a major impact on experimental results, so we strive to reduce the variability [7, 8]. The same person makes all of the helicopters using the same scissors and ruler. The helicopters were dropped from the same height of six meters. A higher or lower starting point would affect flight time, and this could throw off the results. The helicopters must also be held and released the same way, or variation in our data might be the effect of the release method and not the design of the helicopter [9].

The Minitab worksheet below (table 3) contains the experimental output results listed under "Flight time", in the last column.

Table 3. The experimental results listed in column flight time.

	StdOrder	RunOrder	CenterPt	Blocks	Paper type	Rotor length (cm)	Leg length (cm)	Leg width (cm)	Paper clip on	Flight time
1	2	1	1	1	Heavy	7,5	7,5	3,2	No	4,74
2	12	2	1	1	Heavy	8,5	7,5	5,0	No	5,28
3	5	3	1	1	Light	7,5	12,0	3,2	No	4,68
4	15	4	1	1	Light	8,5	12,0	5,0	No	5,61
5	13	5	1	1	Light	7,5	12,0	5,0	Yes	4,83
6	16	6	1	1	Heavy	8,5	12,0	5,0	Yes	4,95
7	1	7	1	1	Light	7,5	7,5	3,2	Yes	5,94
8	7	8	1	1	Light	8,5	12,0	3,2	Yes	5,40
9	10	9	1	1	Heavy	7,5	7,5	5,0	Yes	4,71
10	6	10	1	1	Heavy	7,5	12,0	3,2	Yes	3,81
11	11	11	1	1	Light	8,5	7,5	5,0	Yes	5,97
12	4	12	1	1	Heavy	8,5	7,5	3,2	Yes	4,92
13	8	13	1	1	Heavy	8,5	12,0	3,2	No	4,86
14	3	14	1	1	Light	8,5	7,5	3,2	No	6,90
15	14	15	1	1	Heavy	7,5	12,0	5,0	No	4,62
16	9	16	1	1	Light	7,5	7,5	5,0	No	6,30

To help us interpret the results, Minitab provides main effects and interaction plots. Since we have already the results, Minitab automatically selects the factors used in our model: Paper type, Rotor length, Leg length, Leg width, Paper clip on leg and it gives us plots of the significant main effects and interactions. The main effects plot (figure 3) shows the results of changing from one setting to another for each factor.

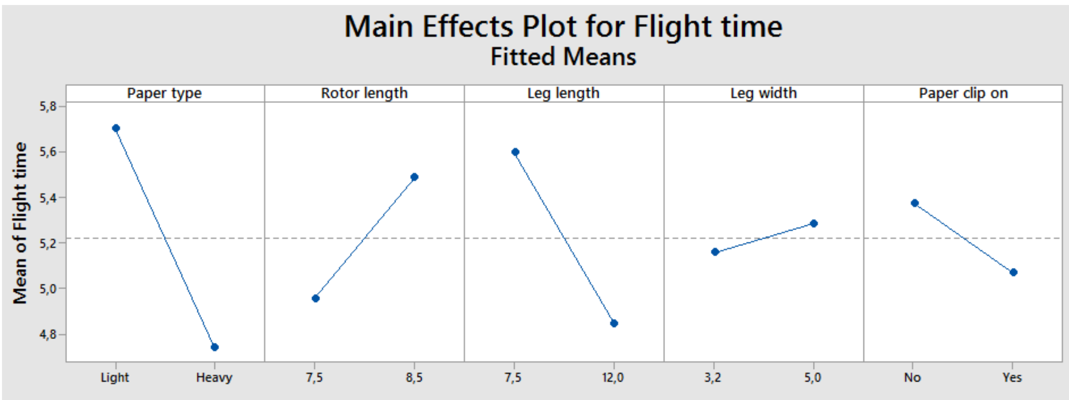

Figure 3. Main effects plot for flight time.

As one can see, the greatest influence has the paper type followed by the length of the leg and the length of the rotor. The smallest influence is given by the leg width.

The interaction plot shows the interactions between the factors, as shown in figure 4.

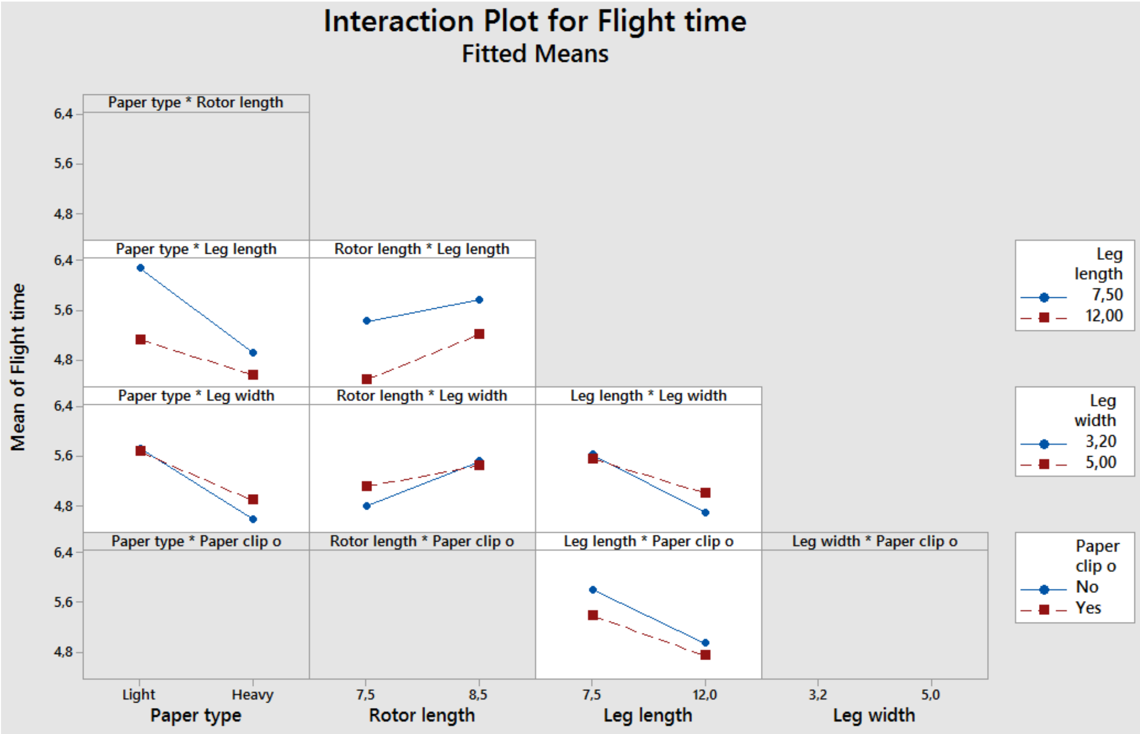

Figure 4. Interaction plot for flight time.

Finally, we can use the Response Optimizer to find the combination of factor settings that will give us the longest flight time. The optimizer produces the following graph (figure 5) showing the optimal factor settings in red, and the predicted response for helicopters made with those settings in blue.

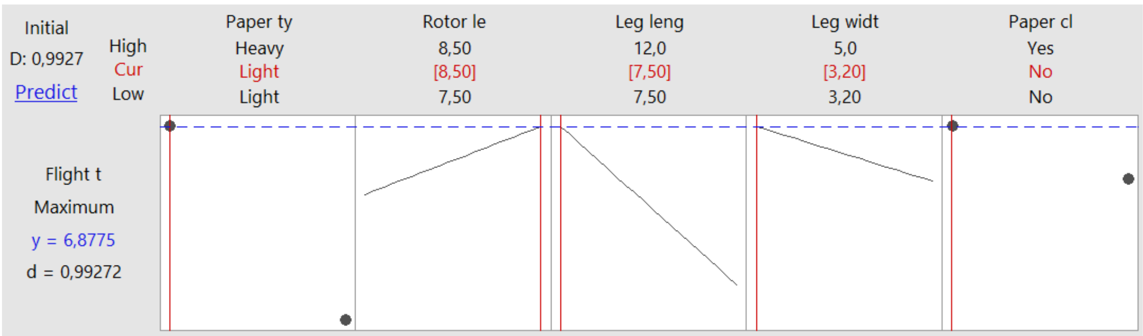

Figure 5. The optimal factor settings in red, and the predicted response in blue.

5. Conclusions

When performing experimental design it is wished to identify the effects of various parameters on the response of the product. In this paper two approaches were followed: one with the full factorial plan, in which we considered that the factors had only two levels and the second with the fractional factorial plan using the Taguchi tables. At the end of the experimental design, a model of the global behavior is available. At this point it can be used to carry out more refined simulations.

As an example, an experimental design of a paper helicopter is performed having the flight time as the desired output for the response variable. For the collected data our analysis indicates that the optimal helicopter settings are: lighter paper, longer rotor length, shorter leg length, slimmer leg width, without any use of paperclips on the leg.

6. References

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