Development of a tool for the easy determination of control factor interaction in the Design of Experiments and the Taguchi Methods

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Abstract — In recent years, the Design of Experiments (hereafter, DOE) and the Taguchi Methods have been used to decide optimum processing conditions with narrow dispersion and achieve robust designs. However, when large interactions between several control factors are present, since they behave as confounding variables, the estimation accuracy is significantly reduced and making practical use of the DOE and Taguchi Methods can be extremely difficult in some cases. As a common countermeasure, calculation accuracy is confirmed by comparing, through the S/N ratio and sensitivity results, the best and worst gain results. This can be of great harm in terms of time and labor and, if the difference between the best and worst gain results is large, could result in the Taguchi Methods estimations being ignored. In this study, a tool for the easy determination of control factor interactions in the DOE and the Taguchi Methods was developed and evaluated. Then a software of the tool was a developed and evaluated under several mathematical models. It was concluded that: (1) a usable tool for the easy determination of control factor interactions in the DOE and the Taguchi Methods was developed; (2) The tool was able to determine control factor interactions in DOE or the Taguchi Methods.

Keywords— Design of Experiments, Taguchi Methods, innovation, innovative tool, software, optimum condition.

1 Introduction

In recent years, the Design of Experiments (hereafter, DOE) and the Taguchi Methods have been used to decide optimum processing conditions with narrow dispersion and achieve robust designs [1], [2], [3]. Usually, the DOE procedure first defines the design parameters to be used. Second, design parameters are used as control factors and all possible control factor combinations are compressed in an orthogonal table. Third, experimentation or CAE simulations are done according to the aforementioned orthogonal table. Finally, the obtained data is summarized and the optimum control factors are selected. On the other hand, the Taguchi Methods follows the same fashion until the orthogonal table step. Here, experiments or CAE simulations are performed in the orthogonal table and include the influence of error factors (hereafter, noise factors). The average and the standard deviation regarding all the possible control factor combinations are calculated to obtain the S/N ratio. Thus, the optimum control factor selection stages in the Taguchi Methods includes the noise factors. Here, the ideal robust design is not influenced by noise factors and, as a consequence, most designers actively search for the combination of control factors that yield a large SN ratio through a good design parameter selection. However, when large interactions between control factors are present, since interactions behave as confounding variables, the estimation accuracy is significantly reduced and making practical use of the DOE and Taguchi Methods can be extremely difficult in some cases. As a common countermeasure, calculation accuracy is confirmed by comparing, through the S/N ratio and sensitivity results, the best and worst gain results. This can be of great harm in terms of time and labor and, if the difference between the best and worst gain results is large, could result in the Taguchi Methods estimations being ignored. In this study, a tool for the easy determination of control factor interactions in the DOE and the Taguchi Methods was developed and evaluated. Specifically, the Level 1 of each control factor was intentionally set to be zero (0) in the orthogonal table in order to obtain functions that are not influenced by control factor interactions. The comparison between the aforementioned functions and conventional DOE orthogonal table functions was then used as an assessment criterion, under several mathematical models, to prove the presence of control factor interaction as well as to determine interacting control factors.

2 Determination of Control Factor Interactions

A. General Description of the Taguchi Methods

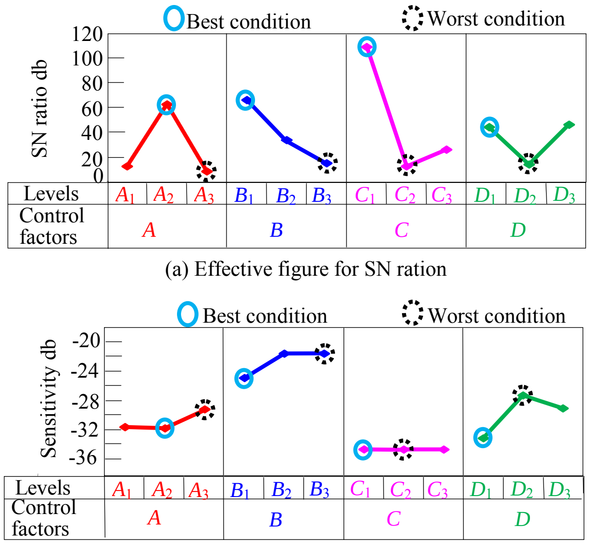
The Taguchi Methods are commonly used, based on a small number of experiments, to choose ideal design parameter combinations that exhibit tight dispersion results. In order to explain the current research, it is necessary to clarify the generalities of the Taguchi techniques in this section [4], [5], [6], [7]. In Table 1, it is possible to observe that design parameters are considered to be the control factors under multiple categories and levels. Noise factors, also regarded as error factors, are the factors that cause experimental result variability and are also included in Table 1. This categorization of control factors can then be extended under a packed orthogonal table to recreate every possible experimental control factor combination as well as the generated noise factor results. As a result, DOE and the Taguchi techniques can be a more time and cost effective alternative to conventional experimentation [8].

Table 1. Example of a control and noise factors set

Control factors				
Name	*A*	*B*	*C*	*D*
Levels	A_1	B_1	C_1	D_1
	A_2	B_2	C_2	D_2
	A_3	B_3	C_3	D_3
Noise factors				
Name	*N*			
Levels	N_1	N_2	N_3	

Table 2. A Taguchi Methods orthogonal array with SN ratio and Sensitivity

Trial No.	Control factors				Result with noise factors			SN ratio (db)	Sensitivity (db)
	A	*B*	*C*	*D*	N_1	N_2	N_3		
1	A_1	B_1	C_1	D_1	2.7	2.6	2.4	24.5	8.2
2	A_1	B_2	C_2	D_2	2.3	2.2	2.0	23.0	6.7
3	A_1	B_3	C_3	D_3	2.1	1.9	2.0	26.0	6.0
4	A_2	B_1	C_2	D_3	3.3	3.1	3.0	26.2	9.9
5	A_2	B_2	C_3	D_1	4.6	4.4	4.5	33.1	13.1
6	A_2	B_3	C_1	D_2	3.3	3.3	3.0	25.3	10.1
7	A_3	B_1	C_3	D_2	2.1	2.3	2.4	23.4	7.1
8	A_3	B_2	C_1	D_3	3.1	3.2	3.1	34.7	9.9
9	A_3	B_3	C_2	D_1	4.7	5.1	4.9	27.8	13.8



(b) Effective figure for Sensitivity

Fig. 1. Relationship between (a) SN ratio or (b) Sensitivity at each level of each control factor (The best condition was assumed to be the smallest possible final function value)

Different to DOE, where noise factors are disregarded, the Taguchi techniques defines the average value and standard deviation in the obtained experimentation, or simulation, results and calculates the SN ratio and Sensitivity parameters. These parameters are obtained by the equations (1) and (2).

$$\text{SN ratio (db)} = 10 \log (\mu^2 / \sigma^2) \quad (1)$$

$$\text{Sensitivity (db)} = 10 \log \mu^2 \quad (2)$$

Where μ is the average value and σ is the standard deviation present in the obtained experimentation, or simulation, results. This allows the user to develop a compilation as shown in Figure 1. Here, the combination of control components that shown the best SN results is sought. The combination is also selected so that it is not affected by noise variables. For instance, in Table 2 the average value and the standard deviation regarding all possible parameter combinations yield 18 SN ratio and Sensitivity calculations. with. Moreover, the addition theorem in the Taguchi Methods is used for calculating the results for all combinations. For example, when *m* is a control factor and *n* is the control factor level, SN ratio SN_{mn} and Sensitivity S_{mn} are the SN ratio and Sensitivity of control factor *m* and level *n*. Furthermore, the SN ratio $SN_{a4 \cdot b2 \cdot c1 \cdot d3 \cdot e2 \cdot f1 \cdot g2}$ and the Sensitivity $S_{a4 \cdot b2 \cdot c1 \cdot d3 \cdot e2 \cdot f1 \cdot g2}$ use the a4, b2, c1, d3, e2, f1, g2 control factors (a, b, c, d, e, f, and g) and defined levels (1, 2, 3, 4, 5 and 6). Here, the addition theorem is used to obtain both parameters in equations (3) and (4). (Where SN_{ave} and S_{ave} are the SN ratio and the Sensitivity values average, respectively).

$$SN_{a4 \cdot b2 \cdot c1 \cdot d3 \cdot e2 \cdot f1 \cdot g2} = SN_{a4}+SN_{b2}+SN_{c1}+SN_{d3}+SN_{e2}+SN_{f1}+SN_{g2}-(7-1)\,SN_{ave} \quad (3)$$

$$S_{a4 \cdot b2 \cdot c1 \cdot d3 \cdot e2 \cdot f1 \cdot g2} = S_{a4}+S_{b2}+S_{c1}+S_{d3}+S_{e2}+S_{f1}+S_{g2}-(7-1)\,S_{ave} \quad (4)$$

(b) Effective figure for SN ration

Finally, in the case of DOE, experimentation or simulation is bounded to the generated orthogonal table and the optimum control factors selected serve to decide the functionality of the procedure.

It should be mentioned that the CAE simulations could take part in this methodology to reduce assessment times and accelerate the technology development process. CAE simulations could be considered as support tool for the experimentation part of the Taguchi Methods. Given that CAE simulations can calculate several physical phenomena such as static, dynamic, thermal, vibration, fluid flow, large deformation phenomena. Which in return could recreate cutting, press forming, crash or explosion experiments. Moreover, control factors used in the Taguchi Methods can, mostly, be directly inputted in CAE simulations. The same happens with noise factors such as temperature and time dependence or other boundary conditions.

B. Control Factor Confounding Behavior Setback

An important setback that limits the aforementioned method is the that when large interactions between control factors are present, the estimation accuracy is significantly reduced and making practical use of the DOE and Taguchi Methods can be extremely difficult in some cases. Here, equations (3) and (4) could show have large errors and lack value during the optimum condition estimation and selection process. As a co mmon countermeasure, calculation accuracy is confirmed by comparing, through the S/N ratio and sensitivity results, the best and worst gain results. This can be of great harm in terms of time and labor and, if the difference between the best and worst gain results is large, could result in the Taguchi Methods estimations being ignored. This methodology can prove the existence of interactions but is not able to determine which control factors are under interaction. In this regard, interactions between control factors behave as confounding variables and neglecting them would cause a bogus association between control factors and, thus, generate the aforementioned estimation inaccuracy. Thus, a method to determine control factor interactions was required.

C. Algorithm for Control Factor Interaction Determination

In this section, an algorithm for the easy determination of control factor interaction in DOE and the Taguchi Methods was developed. Here, it is necessary to consider that function or ideal function, and their values, refer to a mathematically-defined ideal relationship under Taguchi. The developed algorithm consisted in setting a level value of 0 (Zero) in each control factor in order to observe that the final function did not present any influence due to control factor interaction. The tool was used its property for the algorithm. For instance, in Table 3, control factors *A*, *B* and *C* were defined and

Table 3. Orthogonal table in experimental

L4	Control factors			Function F
	A	B	C	
No.1	A_1	B_1	C_1	F_1
No.2	A_1	B_2	C_2	F_2
No.3	A_2	B_1	C_2	F_3
No.4	A_2	B_2	C_1	F_4

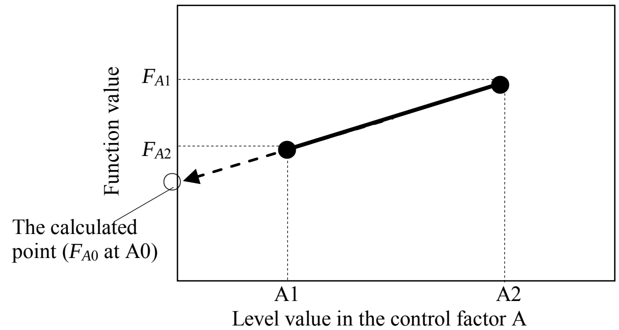


Fig. 2. Effective figure of the control factor (control factor A)

two levels for each factor were defined as A_1, A_2, B_1, B_2, C_1 and C_2 respectively. The L4 orthogonal table shown uses the control factors and those levels for DOE or the Taguchi Methods. The function *F* is the final result of the experiment or the CAE simulations in DOE or the Taguchi Methods and is included in the orthogonal table. The mathematical model in equation (5) defined function F as follows,

$$F_L = 5A_S + 2B_T + 3C_M - 0.1\, A_S\, B_T \tag{5}$$

Where A_S and B_T are the control factors with the influence from the control factor interaction. The terms *L*, *S*, *T*, *M* could take a value of 1 or 2. The relationship between the control factors and the final function used was "$F_L = 5A_S + 2B_T + 3C_M$". However, this relationship is affected by the influence from the control factor interaction, described as "$- 0.1\, A_S\, B_T$ in equation (5). This equation is supposed to yield the most desirable conditions when the final function F is obtained. Therefore the minus value "－" is used for the control factor interaction calculation. Final functions F_{A1}, F_{A2}, F_{B1}, F_{B2}, F_{C1} and F_{C2} for levels A_1, A_2, B_1, B_2, C_1 and C_2 was calculated by equations (6) because of the orthogonal table property.

$$\left.\begin{aligned} F_{A1} &= (F_1 + F_2)/2 \\ F_{A2} &= (F_3 + F_4)/2 \\ F_{B1} &= (F_1 + F_3)/2 \\ F_{B2} &= (F_2 + F_4)/2 \\ F_{C1} &= (F_1 + F_4)/2 \\ F_{C2} &= (F_2 + F_3)/2 \end{aligned}\right\} \tag{6}$$

When each level value for the control factors *A*, *B* and *C* becomes zero "0", the final functions F_{A0}, F_{B0} and F_{C0} can be calculated by the equation (7).

$$\left.\begin{aligned} F_{A0} &= F_{A1} - \frac{F_{A2} - F_{A1}}{A_2 - A_1} A_1 \\ F_{B0} &= F_{B1} - \frac{F_{B2} - F_{B1}}{B_2 - B_1} B_1 \\ F_{C0} &= F_{C1} - \frac{F_{C2} - F_{C1}}{C_2 - C_1} C_1 \end{aligned}\right\} \tag{7}$$

In this section, the number of the each level was only two and pose a simple calculation. However, when the number becomes larger, an array setup would be more convenient. Here, six trials, as shown in Table 4, were performed. Moreover, except for the level value = 0, the other levels are kept the orthogonal property in Table 4. On the other hand, when the control factor level at *A*, *B* and *C* becomes zero "0", those final functions $F_{A0'}$, $F_{B0'}$ and $F_{C0'}$ can calculated by the equation (8) and the new trials.

$$\left.\begin{aligned} F_{A0}' &= (F_{A01}' + F_{A02}')/2 \\ F_{B0}' &= (F_{B01}' + F_{B02}')/2 \\ F_{C0}' &= (F_{C01}' + F_{C02}')/2 \end{aligned}\right\} \quad (8)$$

In Table 5, F_{A0}'and F_{B0}' have no control factor interaction influence in spite of the control factor interaction between control factors *A* and *B*. F_{B0}'and F_{C0}' have no control factor interaction influence, even though there is a control factor interaction between control factors *B* and *C*. And F_{A0}'and F_{C0}' are not influenced by the control factor interaction in spite of the control factor interaction between control factors A and C. Because new trials were used for the calculation. Finally, the calculated final functions F_{A0}, F_{B0} and F_{C0} are compared with the trial final functions $F_{A0'}$, $F_{B0'}$ and $F_{C0'}$ respectively. Here, the control factor interaction and the control factors under reciprocal interaction can be calculated as shown in Table 6.

Table 4. Trial data without control factor interaction

Particularity of the trial set	Trial No.	Control factors A	Control factors B	Control factors C	Function F
Trial data without interaction from control factor A	No.1'	**0**	B_1	C_1	F_{A01}'
	No.2'	**0**	B_2	C_2	F_{A02}'
Trial data without interaction from control factor B	No.3'	A_1	**0**	C_1	F_{B01}'
	No.4'	A_2	**0**	C_2	F_{B02}'
Trial data without interaction from control factor C	No.5'	A_1	B_1	**0**	F_{C01}'
	No.6'	A_2	B_2	**0**	F_{C02}'

Table 5. Function F_{A0}', F_{B0}' and F_{C0}' without control factor interaction effect at level value = 0

Equation (4)	Control factors without interaction effects
F_{A0}'	A (A and B or A and C)
F_{B0}'	B (A and B or B and C)
F_{C0}'	C (A and C or B and C)

Thus,
F_{A0}'and F_{B0}' are not influenced in the presence of control factor interaction between control factors A and B.
F_{B0}'and F_{C0}' are not influenced in the presence of control factor interaction between control factors B and C.
F_{A0}'and F_{C0}' are not influenced in the presence of control factor interaction between control factors A and C.

Table 6. Control factor interaction assessment criteria

Conditions	Control factor interaction
$F_{A0}' = F_{A0}$, $F_{B0}' = F_{B0}$ and $F_{C0}' = F_{C0}$	No interaction
$F_{A0}' = F_{A0}$, $F_{B0}' = F_{B0}$ and $\mathbf{F_{C0}' \neq F_{C0}}$	Control factor interaction between control factors A and B.
$\mathbf{F_{A0}' \neq F_{A0}}$, $F_{B0}' = F_{B0}$ and $F_{C0}' = F_{C0}$	Control factor interaction between control factors B and C.
$F_{A0}' = F_{A0}$, $\mathbf{F_{B0}' \neq F_{B0}}$ and $F_{C0}' = F_{C0}$	Control factor interaction between control factors A and C.

3 A Software using the Proposed Algorithm

A software that follows the flowchart of Fig. 3 was made by using the proposed algorithm. We present it in the Appendix (last page of the paper). The calculated final functions F_{A0}, F_{B0} and F_{C0} are calculated in the Part I, and the trialed final functions $F_{A0'}$, $F_{B0'}$ and $F_{C0'}$ are calculated in the Part II. After this, control factor interaction and the control factors involved are determined by using Table 6. If there are control factor interactions in the control factors, the control factors are removed, new control factors are set and checked for the new control factor interactions. If there is no more control factor interactions, then DOE or the Taguchi methods are performed [9].

4 Algorithm Evaluation and Consideration

A. Evaluation through Defined Mathematical Models

The software was then evaluated by the mathematical model using the equation (5). This linear equation consists of the control factors *A*, *B* and *C*. Here, the control factors *A* and *B* influence to the control factor interaction final function. The control factors, levels and each level value are shown in Table 7. The functions *F* are calculated for the final result by using the equation (5) and Table 7.

Table 7. Control factors

Control factors	Level 1	Level 2
A	1	5
B	20	30
C	3	9

Table 8. Orthogonal table and functions

L4	Control factors			Functions F
	A	B	C	
No.1	1	20	3	52
No.2	1	30	9	89
No.3	5	20	9	82
No.4	5	30	3	79

Table 9. Evaluation results using 1st model (Interaction between the control factors A and B)

Mathematical model: $F_L = 5A_S + 2B_T + 3C_M - 0.1\,A_S\,B_T$ (Where *L*, *S*, *T* and *M* = 1 or 2)			
F_{A0} = 68	F_{A0}'= 68	Equal	Assessment: Control factors A and B have a reciprocal interaction. (see Table 6)
F_{B0} = 33	F_{B0}' = 33	Equal	
F_{C0} = 55.5	F_{C0}'= 56.5	**Not equal**	

Table 10. Evaluation results using 2nd model (Interaction between the control factors B and C)

Mathematical model: $F_L = 5A_S + 2B_T + 3C_M - 0.2B_T\,C_M$ (Where *L*, *S*, *T* and *M* = 1 or 2)			
F_{A0} = 33.5	F_{A0}'= 35	**Not equal**	Assessment: Control factors B and C have a reciprocal interaction. (see Table 6)
F_{B0} = 33	F_{B0}' = 33	Equal	
F_{C0} = 65	F_{C0}'= 65	Equal	

Table 11. Evaluation results using the 3rd model (Interaction between the control factors A and C)

Mathematical model: $F_L = 5A_S + 2B_T + 3C_M - 0.2\,A_S\,C_M$ (Where *L*, *S*, *T* and *M* = 1 or 2)			
F_{A0} = 68	F_{A0}'= 68	Equal	Assessment: Control factors A and C have a reciprocal interaction. (see Table 6)
F_{B0} = 23.4	F_{B0}' = 28.2	**Not equal**	
F_{C0} = 65	F_{C0}'= 65	Equal	

Then the calculated final functions F_{A0}, F_{B0} and F_{C0} can be calculated by equation (7) and Table 3, and the trialed final functions $F_{A0'}$, $F_{B0'}$ and $F_{C0'}$ can be calculated by equation (8) and Table 4 with the new trials. Then, the calculated final functions F_{A0}, F_{B0} and F_{C0} are compared with the trialed final functions $F_{A0'}$, $F_{B0'}$ and F_{C0} as shown in Table 9. It is concluded from Table 9 that the control factors *A* and *B* had a control factor interaction and that the software can determine the interaction and the involved control factors (*A* and *B*).

In Table 10, a second mathematical model is shown. Here, the control factor interaction was changed so that the control factors *B* and *C* are the focus of the equation. The performed procedure to determine the control factor interaction was the same as the previous model. The software was able to determine the control factor interaction and the interaction and the involved control factors (*B* and *C*).

In Table 10, a second mathematical model is shown. Here, the control factor interaction was changed so that the control factors *A* and *C* are the focus of the equation. The performed procedure to determine the control factor interaction was the same as the previous model. The software was able to determine the control factor interaction and the interaction and the involved control factors (*A* and *C*).

In this section, the mathematical models were linear equations with three control factors (first three terms of the equation) and one control factor interaction using two defined control factors (last equation term). Additionally, the developed program also ran under quadratic, cubic equation and a three-factor interaction constraints.

B. Control Factor Interaction Influence Considerations

Here, the relationship between the interaction magnitude and control factor interaction estimation was investigated as shown in equation (9). The "$-$ P$A_S B_T$" term in the equation is the control factor interaction. When the coefficient P is changed, the influence of the control factor interaction also changes in the mathematical model.

$$F_L = 5A_S + 2B_T + 3C_M - \mathrm{P}\,A_S\,B_T \tag{9}$$

Where A_S and B_T are the control factors with control factor interaction influence; *L*, *S*, *T* , *M* = 1 or 2 respectively.

An evaluation function P_{PA} in the equation (10) was used for the control factor interaction magnitude calculation.

$$P_{PA} = \left| \frac{\mathrm{P}\,A_S\,B_T}{F_L} \right| \times 100 \tag{10}$$

The L4 orthogonal table and the final function F are shown in Table 12. The control factor interaction influence were sorted in

Table 12. Orthogonal table and functions (Control factor interaction influence was handled to evaluate the assessment criteria)

L4	Control factors			Functions F				
	A	B	C	P=0.001 P_{PA} =0.03～0.16 %	P=0.01 P_{PA} =0.3～1.6 %	P=0.1 P_{PA} =3.8～19.2 %	P=0.5 P_{PA} =19.5～395 %	P=1.0 P_{PA} =48.4～268 %
No.1	1	20	3	53.98	53.8	52	44	34
No.2	1	30	9	91.97	91.7	89	77	62
No.3	5	20	9	91.9	91	82	42	-8
No.4	5	30	3	93.85	92.5	79	19	-56

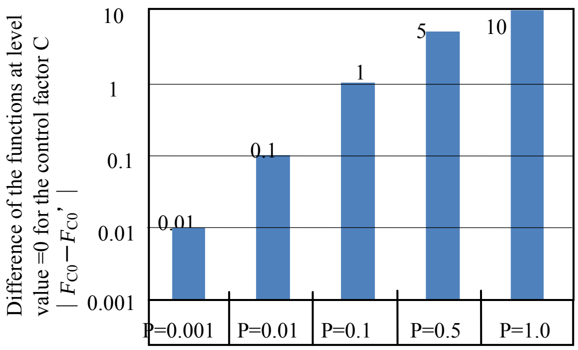


Fig. 4. Evaluation results using equation (9) (Control factor Interaction between control factors A and B)

5 magnitude classes.

Here, the control factors *A* and *B* in the equation (9) influence to the final function for the control factor interaction. In this regard, the procedure performed for the determination of the control factor interaction was used. Here the conditions which F_{A0}' is F_{A0}, F_{B0}' is F_{B0} and F_{C0}'is not F_{C0} should be satisfied in order to determine the interaction between control factors A and B. At this time, F_{A0}' was F_{A0}, F_{B0}' was F_{B0}, however the relationships between the final functions F_{C0}'and F_{C0} were changed to define the control factor interaction influence magnitude.

The relationship between the influence magnitude and the control factor interaction estimation is shown in Fig. 4. For instance, when P was 0.1 (= P_{PA} is from 3.8 % to 19.2 %) F_{C0}' clearly was not equal to F_{C0}. Thus, the developed software can determine the control factor interaction and the involved control factors *A* and *B*. However, when P is 0.01 (= P_{PA} is from 0.3 % to 1.6 %) or lower, F_{C0}'is close to the value of F_{C0}. Consequently, the software, at this range, the control factor interaction and the involved control factors *A* and *B* cannot be fully determined.

5 Conclusions

In this paper, we have concluded that:

1) A usable tool for the easy determination of control factor interactions in the DOE and the Taguchi Methods was developed.
2) The tool was able to determine control factor interactions in DOE or the Taguchi Methods.
3) The defined assessment criteria allowed the relationship between the influence magnitude and the control factor interaction estimation to be handled to a certain degree. Here, when the evaluation function P_{PA} for the control factor interactions was under 1.6 %, the control factor interaction estimation was easily determined.
4) The tool was able to increase the practical use of the DOE and the Taguchi Methods, through the determination of control factor interactions, in cases that common countermeasures would not allow.

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APPENDIX

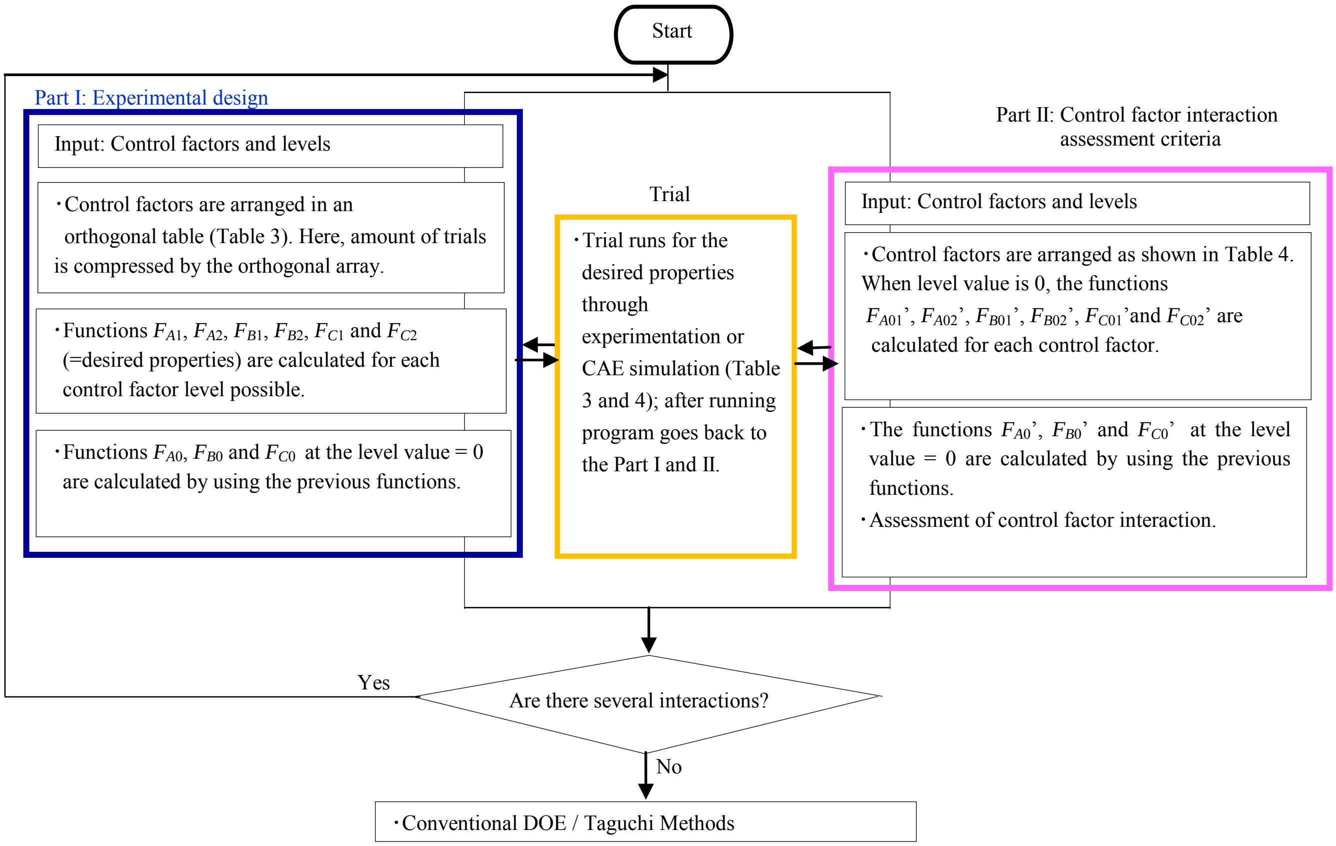

Fig. 3. Flowchart for the control factor interaction determination program