

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 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. 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

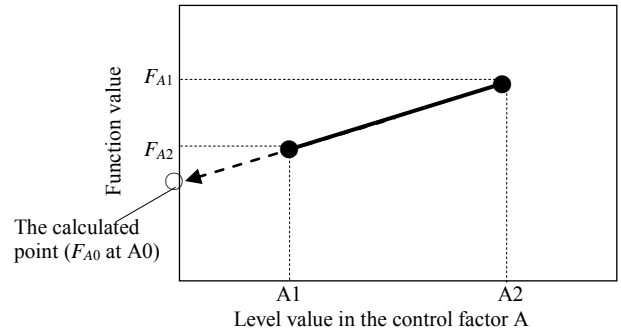


Fig. 2. Effective figure of the control factor (control factor A)

two levels for each factor were defined as A₁, A₂, B₁, B₂, C₁ and C₂ 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 A₁, A₂, B₁, B₂, C₁ and C₂ 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 be 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

Table 4. Trial data without control factor interaction

Particularity of the trial set	Trial No.	Control factors			Function F
		A	B	C	
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 $F_{C0}' \neq F_{C0}$	Control factor interaction between control factors A and B.
$F_{A0}' \neq F_{A0}$, $F_{B0}' = F_{B0}$ and $F_{C0}' = F_{C0}$	Control factor interaction between control factors B and C.
$F_{A0}' = F_{A0}$, $F_{B0}' \neq F_{B0}$ and $F_{C0}' = F_{C0}$	Control factor interaction between control factors A and C.

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.

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

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	

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.

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.

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

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.

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

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=0.01	P=0.1	P=0.5	P=1.0
				$P_{PA}=0.03\sim 0.16\%$	$P_{PA}=0.3\sim 1.6\%$	$P_{PA}=3.8\sim 19.2\%$	$P_{PA}=19.5\sim 395\%$	$P_{PA}=48.4\sim 268\%$
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

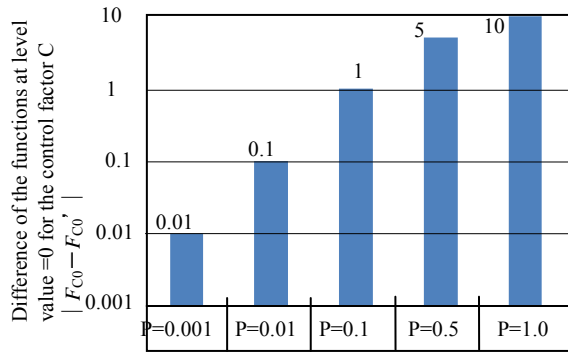


Fig. 4. Evaluation results using equation (9) (Control factor Interaction between control factors A and B)

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.

References

- [1] Fujikawa S., Optimum parameter design using the Taguchi method for Finite-element analysis of 3D forging deformation, Journal of Japan Society for Technology of Plasticity, Vol. 40, No. 466, 1999, pp. 1061-1065 (in Japanese).
- [2] Mizutani J., Hamamoto S., Mukaiyama T., Tanabe I and Yamada Y., Functional evaluation of a micro-polishing process by a combined method of physical and chemical treatments, Journal of Quality Engineering Society, Vol. 10, No. 1, 2002, pp. 84-90 (in Japanese).
- [3] Makino T., Optimization of exhaust port using computer simulation, Proceedings of 13th Quality Engineering Society Conference, 2005, pp.6-9 (in Japanese).
- [4] Tatebayashi, K., Computer Aided Engineering Combined with Taguchi methods, Proceeding of the 2005 Annual Meeting of the Japan Society of Mechanical Engineering, No. 05-1 Vol. 8, 2005, pp. 224-225.
- [5] Sakamoto H., Tanabe I. and Takahashi S., Development for sound quality optimisation by Taguchi methods, Journal of Machine Engineering, Vol. 15, No.2, 2015, pp. 69-81.
- [6] Sugai H., Tanabe I., Mizutani J., Sugii S. and Katayama S., Predictions of optimum forming conditions in press forming using Taguchi method and FEM simulation, Transactions of Japan Society of Mechanical Engineers (Series C), Vol. 72, No.721, 2006, pp. 3044-3050 (in Japanese).
- [7] Yano H., Calculation Method for Taguchi Methods, Nikkan Kogyo Shinbun, 2006, pp. 9-149 (in Japanese).
- [8] Arizono I., Kanagawa A., Ohta H., and Watanabe K., Variable samplig plans for normal distribution indexed by Taguchi's loss function, Naval Research Logistic, Vol. 44, No.6, 1997, pp. 591-603 (in Japanese).
- [9] Tanabe I., Iyama T., Yanagisawa T., and Mizutani J., Development of simulation system on CAE without trial working for products (Manufacture of high precision system using dispersion of error factors), Transactions of Japan Society of Mechanical Engineers (Series C), Vol. 75, No.749, 2009, pp. 203-209 (in Japanese).

APPENDIX

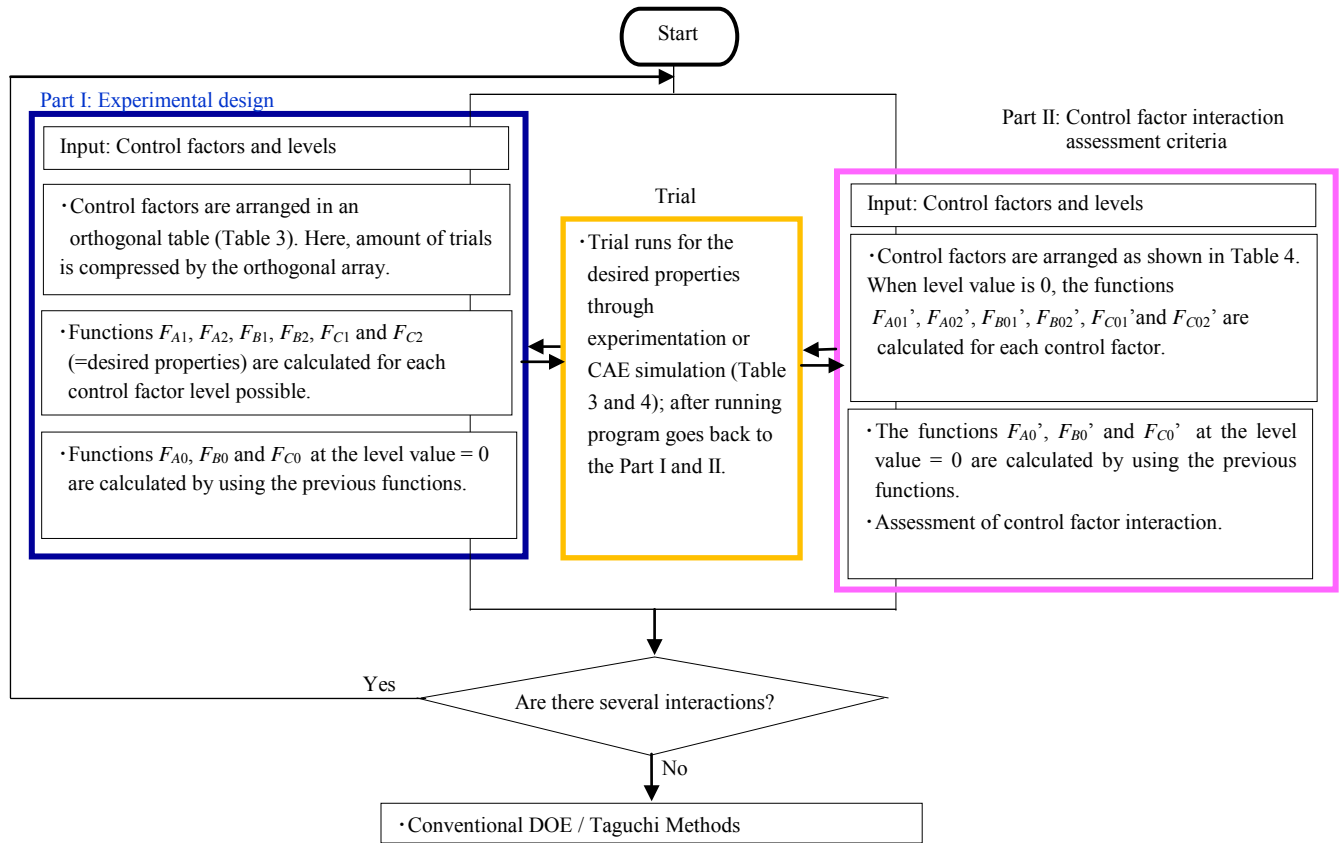


Fig. 3. Flowchart for the control factor interaction determination program