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Invited Paper

Set-Based Design Method Reflecting the Different Designers' Intentions

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Abstract

The previous series of the study have proposed a preference set-based design (PSD) method that enables the flexible and robust design under various sources of uncertainties. In contrast to the traditional design method, this method generates a ranged set of design solutions that satisfy sets of performance requirements. In this study, a system based on PSD is implemented by combination of 3D-CAD and CAE, and the system is applied to a real industrial design problem, i.e., automotive front-side frame. This paper, also, discusses the applicability of the system for obtaining the multi-objective satisfactory design solutions reflecting the different designers' intentions.

Keywords:
Set-Based Design, Design Intention, Flexible and Robust Design, Multi-Objective Design, 3D-CAD

1 INTRODUCTION

The early phase of design called conceptual and preliminary design contains multiple sources of uncertainties in describing design, and nevertheless the decision-making process at this phase exerts a critical effect upon all design properties. Since the late 1980's, concurrent engineering (CE) has brought new possibilities for realizing faster product development, higher quality, lower costs, improved productivity, better custom values, and so on. The traditional design (point-based) practices obtain a point solution within the solution space and then iteratively modify that solution until it meets a satisfactory solution, however, the iterations to refine that solution can be very time consuming. In this iterative process, there is also no theoretical guarantee that the process will ever converge and produce an optimal solution. In addition, using unique point solution does not express information about uncertainties caused by many sources of variations.

The previous series of the study have proposed a preference set-based design (PSD) method that enables the flexible and robust design while incorporating designer's preference structure to resolve the problems of the traditional design methods [1][2]. In contrast to the traditional design methods, this method generates a ranged set of design solutions that satisfy sets of performance requirements.

Meanwhile, various computer-based simulation tools such as 3D-CAD systems and CAE are widely used as designers' everyday design works and have helped propel the CE practice.

In this study, the system based on PSD is implemented by combination of 3D-CAD and CAE. This paper presents the applicability of the system for obtaining the multi-objective satisfactory solutions reflecting the different designers' intentions by applying to a real industrial design problem, i.e., automotive front-side frame problem.

2 SET-BASED DESIGN METHOD

PSD method consists of the set representation, set propagation, set modification, and set narrowing. Figure 1 shows the procedure of the proposed method.

2.1 Set Representation

The representation and manipulation of engineering uncertainties have great importance at the early phase of design. To capture the designer's preference structure on the continuous set, both an interval set and a preference function defined on this set, which is called the "preference number (PN)", are used. The PN is used to specify the design variables and performance requirements, where any shapes of PN are allowed to model the designer's preference structure as shown in Figure 2 as well as the traditional design specifications (e.g., the-larger-the-better, the-center-the-better or the-smaller-the-better). The interval set at the preference level of 0 is the allowable interval, while the interval set at the preference level of 1 is the target interval that the designers would like to meet. Consider a variable, X_i (i = 1, 2, … , m), defined on the real line $\boldsymbol{R}$, and denote an element of X_i by x. Then, the quantified PN (QPN), $\tilde{X}_i$ [3] is defined by:

$$\tilde{X}_i = Q\bar{X}_i \tag{1}$$

where

$$Q \in \{\forall, \exists\} \tag{2}$$

$$\bar{X}_i = \{(x, p_i(x)) \mid x \in X_i, p_i(x): x \to [0,1]\} \tag{3}$$

The QPN uses an interval set and a preference function ($p_i(x)$). In this manner, the designers can incorporate their design intentions into the controllable or uncontrollable variables in defining both possible design space and required performance space. The QPN for describing design solutions and performance requirements are here

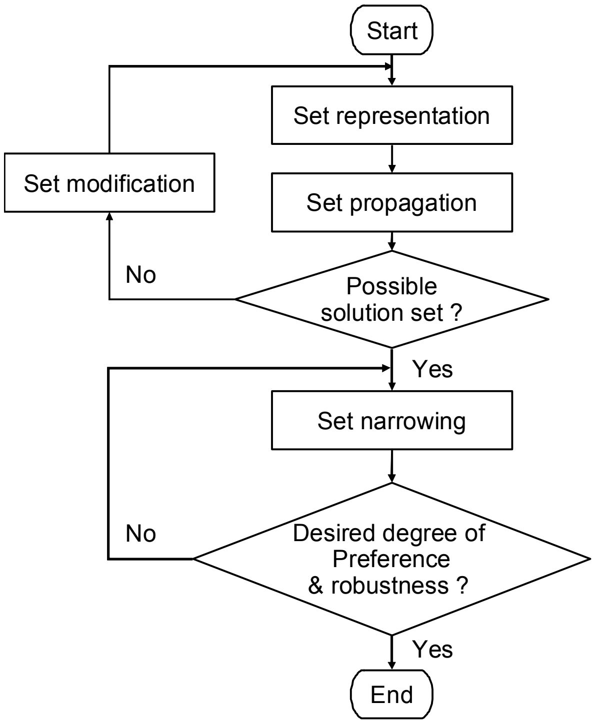


Figure 1: Procedure of the set-based design method.

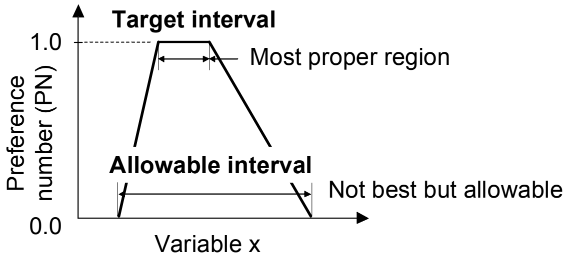


Figure 2: Designer's preference structure.

called the "design QPN" and the "performance QPN, respectively.

2.2 Set Propagation and Set Modification

Set propagation method that combines the decomposed fuzzy arithmetic with the extended interval arithmetic (i.e., Interval Propagation Theorem, IPT [3]) is proposed to calculate the possible performance spaces achievable by the given initial design space. Then, if all the performance variable spaces have the common spaces (i.e., acceptable performance space) between the required performance spaces and the possible performance spaces, there is a feasible subspace within the initial design space. Otherwise, the initial design space should be modified in set modification process.

2.3 Set Narrowing

If the overlapping regions between the possible performance spaces and the required performance spaces exist, there are feasible design subspaces (i.e., not a single point solution) within the initial design space. However, if the possible performance space is not the sub-set of the required performance space, there also exist infeasible subspaces in the initial design space that produce performances outside the performance requirement. Then, the next step is to narrow the initial design space to eliminate inferior or unacceptable design subspaces, thus resulting in feasible design subspaces. To select an optimal design subspace out of those feasible design subspaces, robust design decisions need to be made to make a product's performance insensitive to various sources of variations. The QPN has been also used to define the possible design space by capturing the designer's preference structure. In addition to the design robustness, we should take into account which one is preferred by the designer. The design preference and robustness are evaluated to eliminate infeasible design subspaces.

2.4 Design Metric for Design Preference and Robustness

Measuring design preference

A preference function has been employed to capture varying degrees of preference of a ranged set of possible design solutions and a ranged set of performance requirements. A performance QPN $\tilde{Y}$ is specified to represent the varying degree of desirability of the performance requirement in performance variable *Y*. Then, a preference function, $p_{\tilde{Y}}(y)$, is a function defining the relationship between the degree of desirability (*p*) and the elements (*y*) of a ranged set of performance requirement. When the input QPN of design variables are related to the performance *Y*, the resulting performance will correspondingly be a possibilistic distribution, $q_{\tilde{Y}}(y)$, of the performance *Y*.

In this paper, the design preference index (*DPI*) [4] is adopted to evaluate the performance variation resulting from a range of solutions. Mathematically, the *DPI* is defined as the expected preference function value of design performance within the range of design solutions as depicted in the following form:

$$DPI(\tilde{Y}_i) = E[p(y)] = \int_{y_L^{(0)}}^{y_U^{(0)}} p_{\tilde{Y}}(y) q_{\tilde{Y}_i}(y) dy \qquad (4)$$

Measuring design robustness

Although the *DPI* is a good design metric to measure design solutions with the possibilistic distributions with respect to the varying degree of preference, it often makes incorrect evaluations due to the incapability of measuring the uncertainty of the possibilistic distributions [1].

A new measure of uncertainly have been proposed, what is called the precision and stability index (*PSI*) [2]. The *PSI* could also be used to measure the design robustness and indicates how much of the distribution is close to 0.0 and 1.0. The *PSI* is developed by modifying Shannon's entropy measure [5] and employing a correction factor [6].

$$PSI(\tilde{Y}_i) = C \sum_{y}^{|Y|} PS(q_{\tilde{Y}_i}(y)) \qquad (5)$$

where

$$C = \frac{W}{A} \qquad (6)$$

$$PS(q_{\tilde{Y}_i}(y)) = \begin{cases} -S(q_{\tilde{Y}_i}(y)) + K \\ \quad if\ 0 < q_{\tilde{Y}_i}(y) < 0.5\ or\ 0.5 < q_{\tilde{Y}_i}(y) < 1 \\ K \quad if\ q_{\tilde{Y}_i}(y) = 0\ or\ q_{\tilde{Y}_i}(y) = 1 \\ 0 \quad if\ q_{\tilde{Y}_i}(y) = 0.5 \end{cases}$$

$$S(q(y)) = -q(y)\ln(q(y)) - (1 - q(y))\ln(1 - q(y)) \qquad (7)$$

$$K = -\ln(0.5)$$

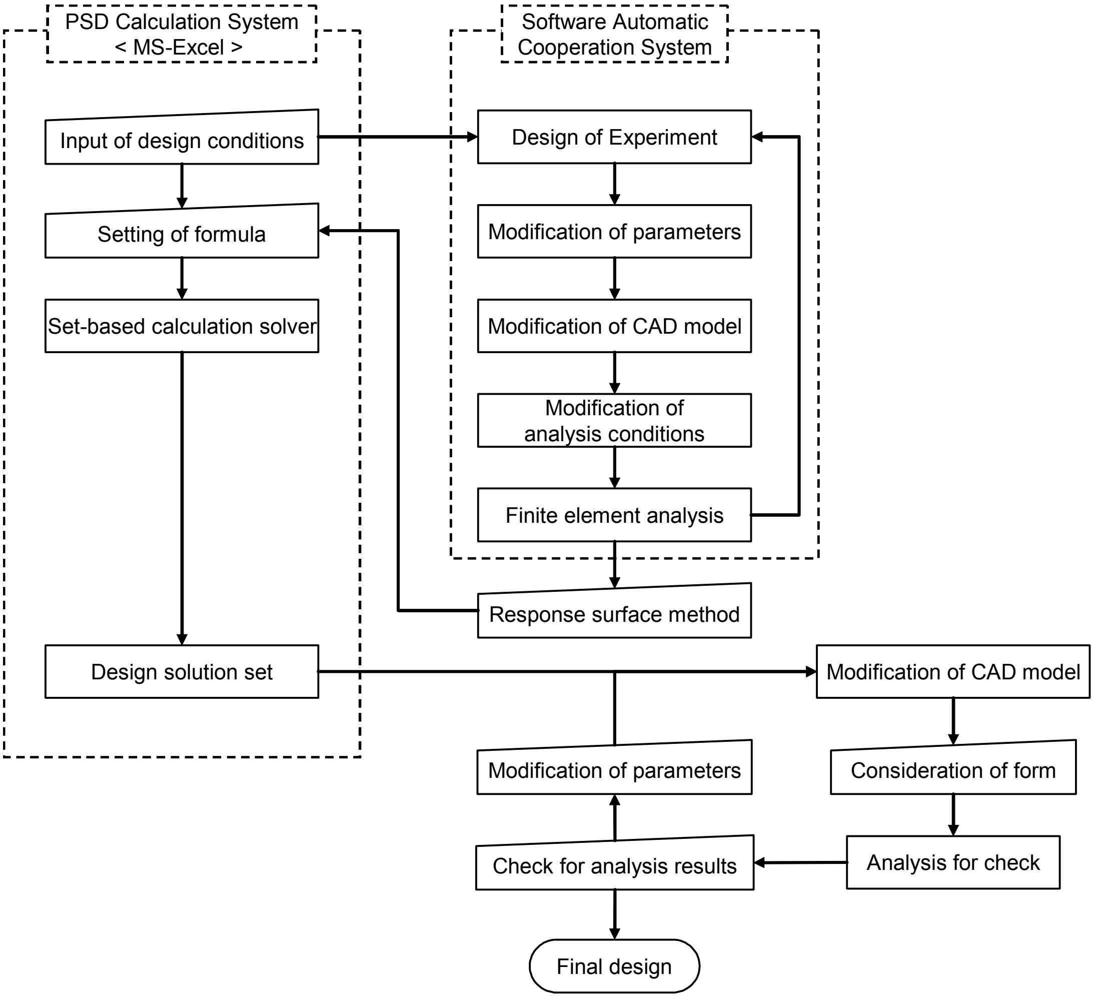


Figure 3: Set-based design system based on 3D-CAD.

where C is a correction factor to make correct measure about the uncertainty degrees of subnormal distributions with different heights [6], W and A denote the width of interval at the preference level of 0 and the area size of distribution, respectively. $S(q(y))$ is Shannon's entropy function. The more values of distribution close to 0 and 1, the larger the *PSI* measures.

Measuring design preference and robustness

This study can measure the preference and robustness, what is called the preference and robustness index (*PRI*), of possibilitistic distributions by combining *DPI* with *PSI*. To provide the relative effectiveness among design alternatives, the *DPI* and *PSI* need to be normalized with respect to the maximum of all *DPI* values and the minimum of all *PSI* values, respectively. The *PRI* is obtained by:

$$\begin{aligned} PRI(\tilde{Y}_i) &= (DPI(\tilde{Y}_i)/\mathrm{Max}_{j=1,\cdots,n}DPI(\tilde{Y}_j)) \\ &\quad \times (\mathrm{Min}_{j=1,\cdots,n}PSI(\tilde{Y}_j)/PSI(\tilde{Y}_i)) \\ &= NDPI \times NPSI \end{aligned} \tag{8}$$

where *NDPI* and *NPSI* indicate the normalized *DPI* and normalized *PSI*, respectively. Since more than one performance variable are commonly considered in the multi-objectives design problem, the *PRI*s for multiple performances need to be aggregated, what is called aggregated *PRI* (*APRI*), to provide the effectiveness of the design alternatives with respect to all performances. A family of parameterized aggregation functions is used for the multi-objective decision making problem, based on the weighted root-mean-power [7]:

$$\begin{aligned} & APRI_s((PRI_1,\omega_1),\cdots,(PRI_n,\omega_n)) \\ & = \left(\frac{\omega_1(PRI_1)^s + \cdots + \omega_n(PRI_n)^s}{\omega_1 + \cdots + \omega_n} \right)^{1/s} \end{aligned} \tag{9}$$

By varying the parameter s, the expression Equation 9 produces some well-known averaging operators: min, harmonic mean (HM), geometric mean (GM), arithmetic mean (AM), quadratic mean (QM), and max.

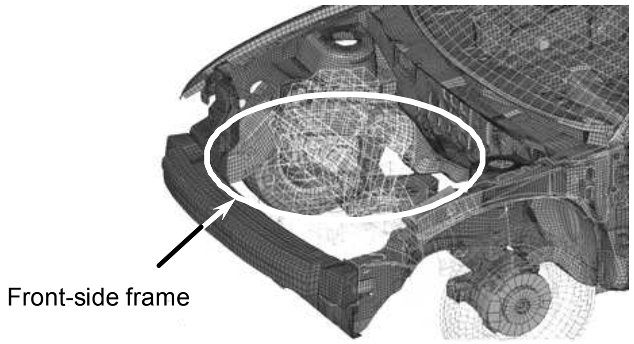
Finally, the set narrowing method first eliminates infeasible or unacceptable design subspaces that produce the performances outside the performance requirement, and then selects an optimal one from a few feasible design subspaces, which are more preferred by the designer and provide better design robustness (i.e., the highest *APRI* measure).

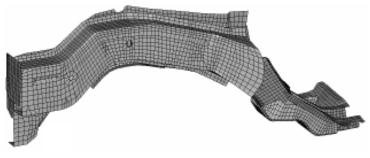
3 APPLICATION TO AUOMOTIVE FRONT-SIDE FRAME

3.1 Set-Based Design System Based on 3D-CAD

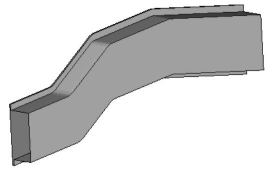
Figure 3 shows the overview of the proposed system. This system consists of a PSD calculation system and a software automatic cooperation system.

The PSD calculation system is implemented by developing an add-in program of Microsoft Excel (MS-Excel). This program is written in Visual Basic. A designer can specify the design QPN and the performance QPN, by directly using MS-Excel interface or initiating a special QPN composer. The performances (i.e., possiblisitic distribution) achievable by the given input design





(b) Published front-side frame



(a) Published automotive body (c) Parametric CAD model

Figure 4: Front-side frame model.

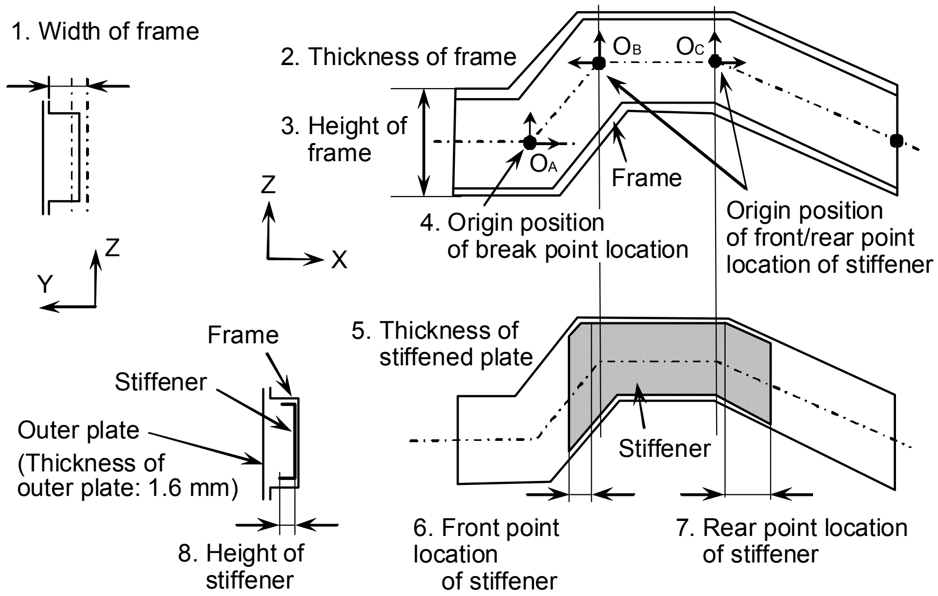


Figure 5: Design variables of front-side frame model.

variables are calculated with the designer's input of the number of decomposition of input the input QPN, and its result is automatically displayed in a new sheet.

The software automatic cooperation system operates a 3D-CAD system and analysis software by cooperating with MS-Excel. The system can activate and execute analysis software and can change the geometric size of 3D-CAD models automatically. In this system, Unigraphics (EDS, Inc.) is used as a 3D-CAD system, and Nastran (MSC, Inc.) is used as FEM analysis software.

The relationship between design variables and performances variables (i.e., surrogate models) is needed for carrying out the PSD calculation. In this paper, the response surface model (RSM) is adopted to build a surrogate model of actual computer simulation, since it is the most well-established meta-modeling technique, and provides closed-form equations as the approximation model. In the RSM, different design parameter value combinations data are selected through design of experiment (DoE) technique and least squares regression analysis is used to fit these data with a polynomial function.

The value of each design variable is changed by using DoE, and then the form of the parametric CAD model is changed. The FEM analysis is carried out with changing the analysis conditions. These operations are repeated for DoE times, and the results of FEM analysis are written into the MS-Excel sheet automatically.

3.2 Setting of Design Problem

In this paper, a design of an automotive front-side frame is chosen to illustrate the effectiveness of the proposed design method for simultaneously obtaining multi-objective satisfactory design solution. The part of automotive front-side frame as shown in Figure 4(b) was extracted from the published automotive body structure of 2.0L displacement [8] as shown in Figure 3(a), and then, the parametric CAD model as shown in Figure 4(c) was created by defining the part sizes representing the form feature of the structure. The present study applies the proposed system to the automotive front-side frame by using this CAD model.

The purpose of this design is to fine the values of eight design variables as shown in Figure 5. Table 1 shows the domains of the design variables, given by designers. Performance requirements include the considerations on five performances, i.e., bending stiffness, tie-down strength, maximum reaction force, average collapse load, and mass.

3.3 Setting Design Intensities of Design Variables and Requirement Functions

To verify how the designers' intentions reflect in the design solutions, the intentions of different three designers are represented as the different design QPN. In this paper, three designers (designer A, B, and C) are defined. The "designer A" emphasizes the performance, the "designer B" emphasizes the balance of the performance and the cost, and the "designer C" emphasizes the cost. Figure 6 shows these designers' design QPN. In this case, the setting method of the designers' intention is explained as an example of the width of frame. The domain of the width of frame in Figure 6(a) is [47, 67] (mm).

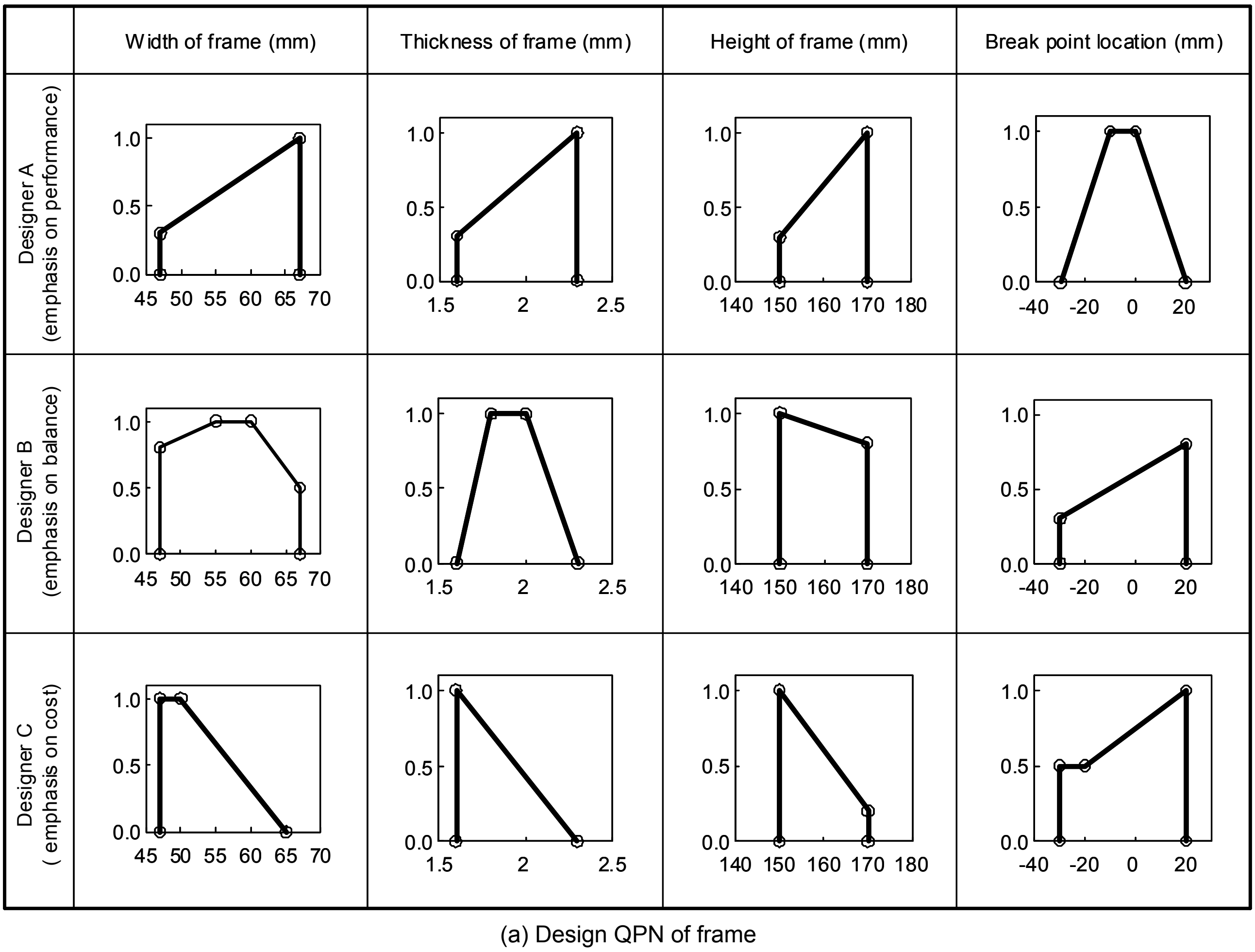
Table1: Setting of design variables.
(coordinates: O_A, O_B, O_C)

No.	Design variables	Domain (mm)
1	Width of frame	[47, 67]
2	Thickness of frame	[1.6, 2.3]
3	Height of frame	[150, 170]
4	Break point location (O_A)	[-30, 20]
5	Thickness of stiffener	[1.0, 2.0]
6	Front point location of stiffener (O_B)	[10, 50]
7	Rear point location of stiffener (O_C)	[10, 100]
8	Height of stiffener	[5, 30]

First, the "designer A", who emphasizes the performance, defines the interval set at the preference level of 1.0 as 67mm that is the widest frame. As a narrow width of frame is difficult to secure the performance, he/she sets the lower preference level. However, the narrowest width 47mm is capable of setting, so the preference level is 0.3.

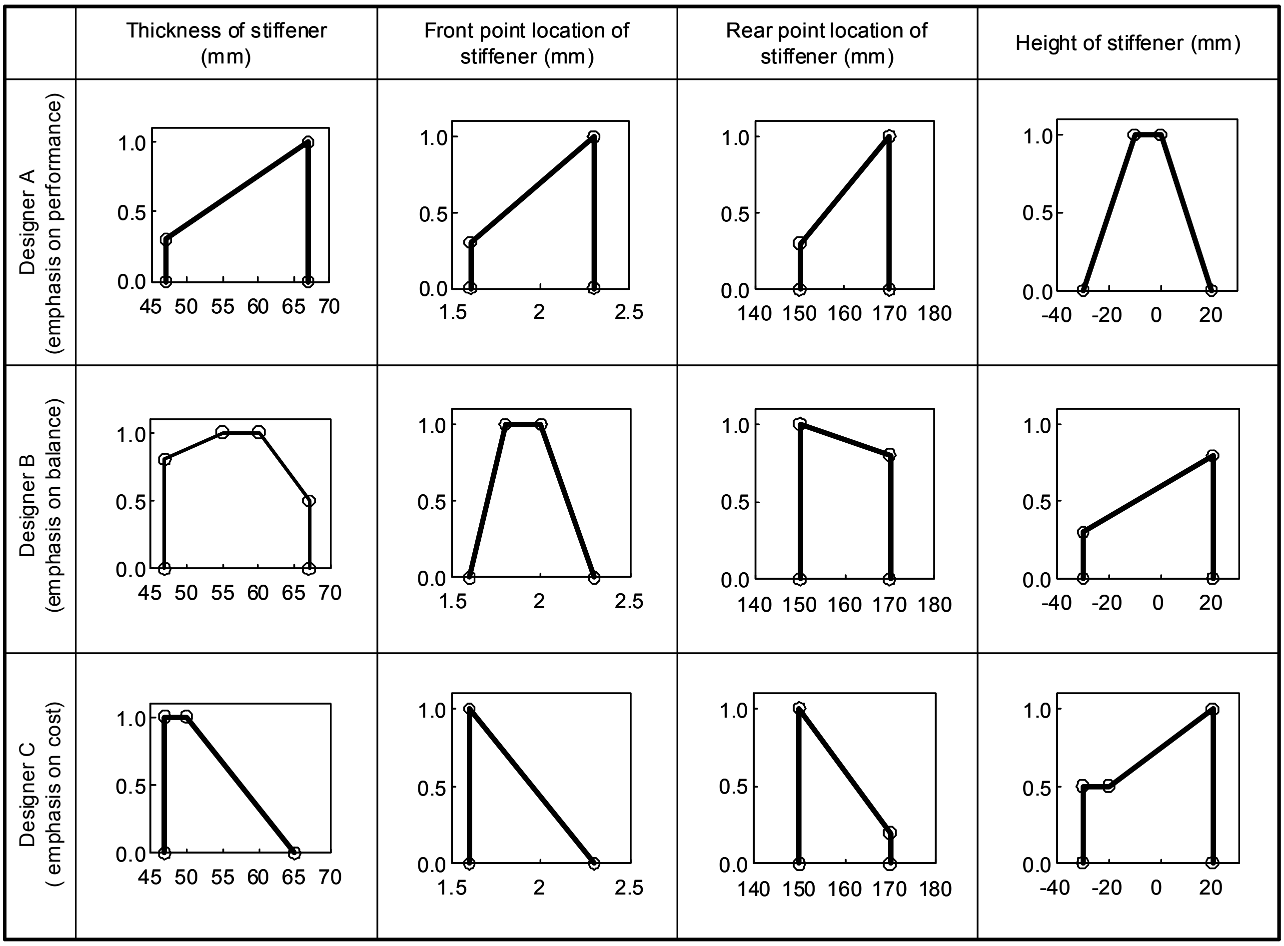
Second, the "designer B", who emphasizes the balance of the performance and the cost, defines the interval set at the preference level of 1.0 as [55, 60] (mm) that is the middle area of the width of frame. He/she sets the lower preference level of both the narrower frame side and the wider frame side. As the narrower frame has an advantage of cost, he sets the higher preference level of the narrower frame than the wider frame. Thus, the preference level of the narrowest width 47mm is 0.8, and the preference level of the widest width 67mm is 0.5.

Finally, the "designer C", who emphasizes the cost, defines the interval set at the preference level of 1.0 as [47, 50] (mm) that is the narrower area of the width of frame. As a wider frame isn't preferable for cost, he/she sets the lower preference level of the frame above 50mm.



(a) Design QPN of frame

Figure 6: Preference of design variables.



(b) Design QPN of stiffener

Figure 6: Preference of design variables.

3.4 Setting Design Intensities of Required Performances

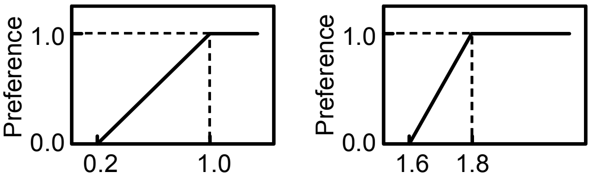
Figure 7 shows three designers' performance QPN. In this paper, the performance QPN are the common requirements to three designers, and the differences of the emphasis of three designers are represented by weighting the each performance requirement.

Figure 7(a) shows the performance QPN of the bending stiffness. The higher the bending stiffness is the better. Considering the conflicting performances, the bending stiffness below 1.0×10^4N/mm is allowable but the preference level is low because the need of adding strength is expected. The bending stiffness below 0.2×10^4N/mm isn't admitted by the past experiences.

Figure 7(b) shows the performance QPN of the tie-down strength. The expected load is the range of [16, 22] (kN), but the strength above 18 kN is preferable because it is possible that the planed body mass increases.

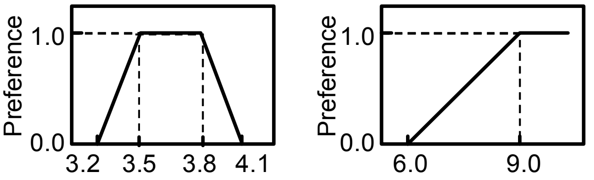
Figure 7(c) shows the performance QPN of the maximum reaction force. Lower limit of force is 3.2×10^5N to utilize the energy absorption of crushable zone effectively at the time of the crash. Upper limit of force is 4.1×10^5N to protect the cabin.

Figure 7(d) shows the performance QPN of the average collapse load. The load above 9.0×10^4N is preferable because the frame absorbs more energy at the first half of the crash. On the other hand, the load below 9.0×10^4N isn't preferable because it's necessary to adjust the structure of the seatbelt for passengers.



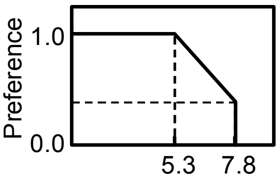
(a) Bending stiffness ($\times10^4$ N/mm)

(b) Tie-down strength ($\times10^4$ N)



(c) Maximum reaction force ($\times10^5$ N)

(d) Average collapse load ($\times10^4$ N)



(e) Mass (kg)

Figure 7: Preference of required performance.

Table 2: Weighting of required performances.

		Emphasis on performance	Emphasis on balance	Emphasis on cost
Bending stiffness		7	2	2
Tie-down strength		10	8	3
Clash	Reaction force	10	4	6
	Collapse load	10	10	6
Mass		3	6	10

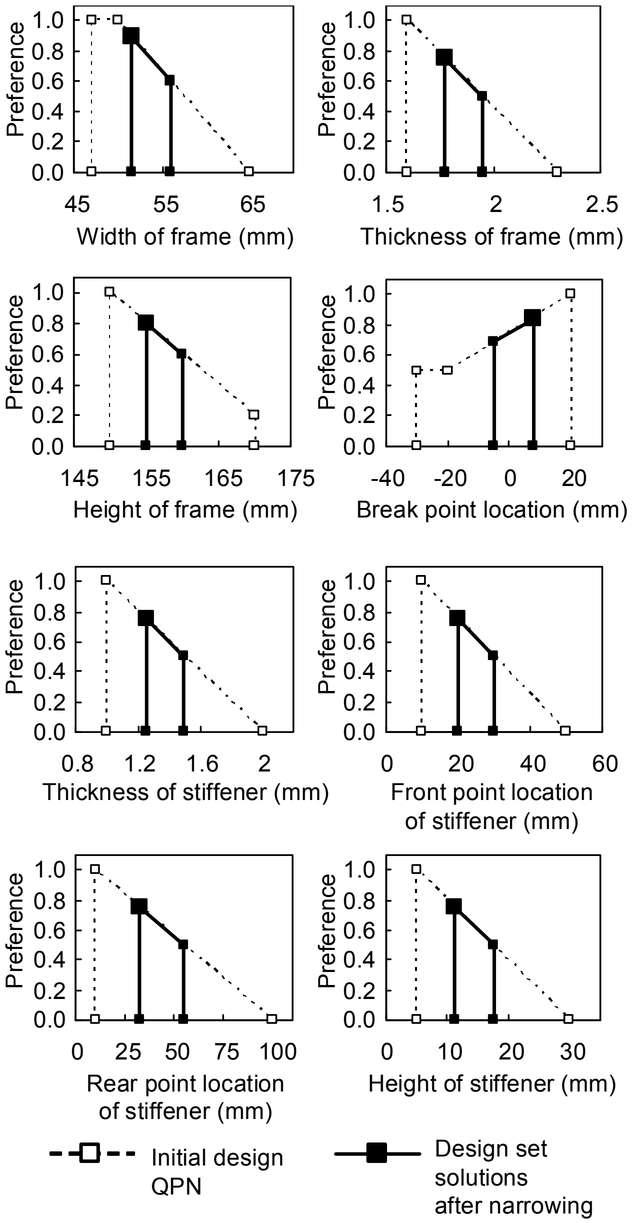


Figure 8: Preference of design variables (Designer C).

Figure 7(e) shows the performance QPN of the mass. The lighter the mass is the better. The mass below 7790g is allowable, but the most lightweight frame in this class is achieved if the mass below 5270g is.

When a design object has various required performances, there are more highly weighted performances or lower weighted performances. To reflect the importance of the required performances in the structure of the front-side frame, the weight of each required performance as shown in Figure 7 is classified. Table 2 shows the weighting factors of required performances. In this paper, three patterns are defined: emphasis on performance, emphasis on balance of performance and cost, and emphasis on cost due to the designers' intentions.

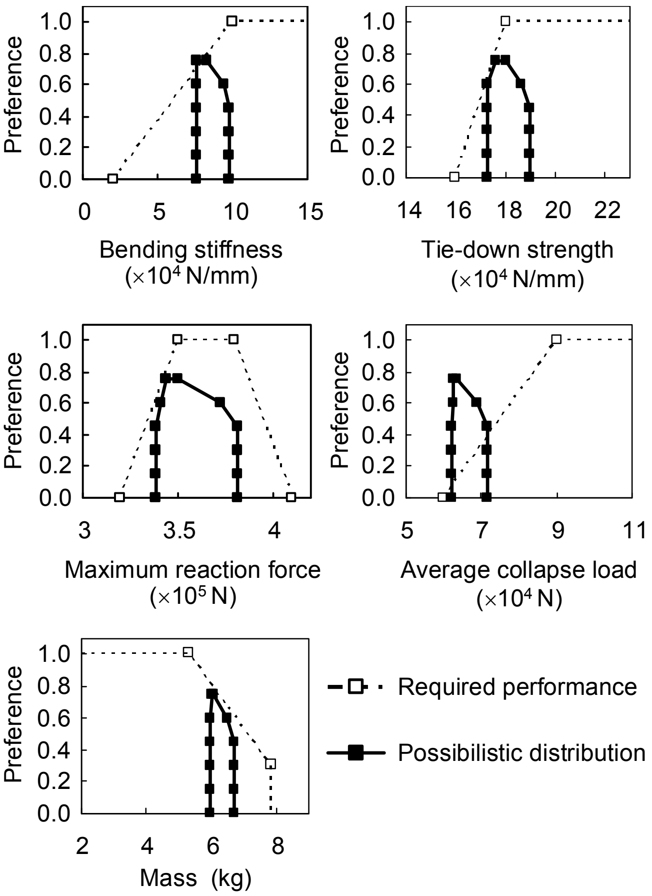


Figure 9: Preferences of design requirements. (Designer C)

3.5 Results and Discussions

Figure 8 and Figure 9 show the ranged set of solutions of design variables and the possibilistic distribution of performances in the case of the "designer C", respectively. Figure 8 indicates that all of the ranged sets of solutions of design variables as shown in solid line are narrowed from the initial preferences of design variables as shown in dotted lines. Figure 9 indicates that all of the possibilistic distributions of performances as shown in solid line are limited within the required performances as shown in dotted lines. These results show that the multi-objective satisfactory design solutions are obtained. The ranged set of solutions that satisfy five requirement performances at the preference level of 0.0 in the case of the "designer A" and "designer B" are shown in Table 3.

Figure 10 compares, in terms of the relation between the mass and the maximum reaction force, performances-oriented solutions (designer A), balance-oriented solutions (designer B) and cost-oriented solutions (designer C). This result indicates that the balance-oriented solutions exist between performances-oriented solutions and cost-oriented solutions.

Table 3: Design set solutions.

Items			Design domain	Designers					
				A Performance		B Balance		C Cost	
				min.	max.	min.	max.	min.	max.
Design variables (mm)	Frame	Width	[47, 67]	57.0	62.0	47.0	52.0	51.5	56.0
		Thickness	[1.6, 2.3]	1.95	2.13	1.95	2.13	1.78	1.95
		Height	[150, 170]	160	165	165	170	155	160
		Break point location	[-30, 20]	-5.0	7.5	7.5	20.0	-5.0	7.5
	Stiffener	Thickness	[1.0, 2.0]	1.75	2.00	1.25	1.50	1.25	1.5
		Front point location	[10, 50]	30.0	40.0	30.0	40.0	20.0	30.0
		Rear point location	[10, 100]	55.0	77.5	32.5	55.0	32.5	55.0
		Height	[5, 30]	26.3	30.0	25.0	30.0	11.3	17.5
Required performance	Bending stiffness (×10^4 N/mm)		Above 0.2	9.81	12.09	6.77	9.06	7.59	9.73
	Tie-down strength (×10^4 N)		Above 1.6	1.79	1.96	1.90	2.07	1.72	1.90
	Maximum reaction force (×10^5 N)		[3.2, 4.1]	3.65	4.08	3.63	4.07	3.39	3.82
	Average collapse load (×10^4 N)		Above 6.0	7.17	8.13	6.91	7.86	6.23	7.18
	Mass (kg)		Below 7.790	6.834	7.569	6.365	7.105	5.985	6.721

In this way, the proposed design method can capture the designers' preference structures and reflect the design intentions of designers in their design solutions.

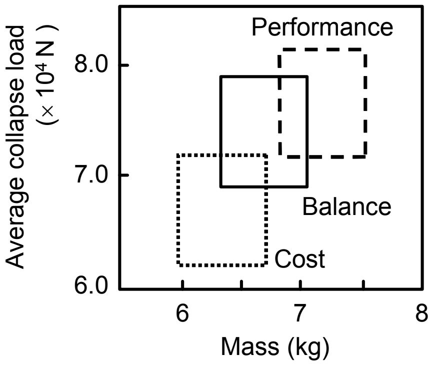


Figure 10: Preferences of design requirements.

4 SUMMARY

In this paper, the concept of preference set-based design (PSD) method is introduced, and the system based on PSD is implemented by combination of 3D-CAD and CAE. The PSD method is an approach to achieve the design flexibility and robustness while incorporating the designers' intentions under various sources of uncertainties.

The implementation system is applied to a real industrial multi-objective design problem (i.e., automotive front-side frame problem) with uncertain parameters in the simulation-based design environment. This presents the possibilities of the system for obtaining the multi-objective satisfactory design solutions reflecting the different designers' intentions.

5 ACKNOWLEDGMENTS

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