

# A Supplementary File for “An Easy-to-use Real-world Multi-objective Optimization Problem Suite”

Ryoji Tanabe, Hisao Ishibuchi\*

*Shenzhen Key Laboratory of Computational Intelligence, University Key Laboratory of  
Evolving Intelligent Systems of Guangdong Province, Department of Computer Science and  
Engineering, Southern University of Science and Technology, Shenzhen 518055, China*

---

## Abstract

This is a supplementary file for “An Easy-to-use Real-world Multi-objective Test Optimization Problem Suite”.

---

## S.1. Details of the RE problems

### S.1.1. RE2-4-1: Four bar truss design problem

The RE2-4-1 problem is to minimize the structural volume ( $f_1$ ) and the joint displacement ( $f_2$ ) of the four bar truss [S.1]. The two objective functions of the RE2-4-1 problem are given:

$$f_1(\mathbf{x}) = L(2x_1 + \sqrt{2}x_2 + \sqrt{x_3} + x_4), \quad (\text{S.1})$$

$$f_2(\mathbf{x}) = \frac{FL}{E} \left( \frac{2}{x_1} + \frac{2\sqrt{2}}{x_2} - \frac{2\sqrt{2}}{x_3} + \frac{2}{x_4} \right), \quad (\text{S.2})$$

where  $x_1, x_4 \in [a, 3a]$ ,  $x_2, x_3 \in [\sqrt{2}a, 3a]$ , and  $a = F/\sigma$ . The four variables determine the length of four bars, respectively. The parameters are given as follows:  $F = 10$  kN,  $E = 2 \times 10^5$  kN/cm<sup>2</sup>,  $L = 200$  cm,  $\sigma = 10$  kN/cm<sup>2</sup>.

---

\*Corresponding author

Email addresses: [rt.ryoji.tanabe@gmail.com](mailto:rt.ryoji.tanabe@gmail.com) (Ryoji Tanabe), [hisao@sustech.edu.cn](mailto:hisao@sustech.edu.cn) (Hisao Ishibuchi)

### S.1.2. RE2-3-2: Reinforced concrete beam design problem

The first objective of the RE2-3-2 problem is to minimize the total cost of concrete and reinforcing steel of the beam [S.2]:

$$f_1(\mathbf{x}) = 29.4x_1 + 0.6x_2x_3, \quad (\text{S.3})$$

$$g_1(\mathbf{x}) = x_1x_3 - 7.735\frac{x_1^2}{x_2} - 180 \geq 0, \quad (\text{S.4})$$

$$g_2(\mathbf{x}) = 4 - \frac{x_3}{x_2} \geq 0, \quad (\text{S.5})$$

where  $x_2 \in [0, 20]$  and  $x_3 \in [0, 40]$ . We determined the ranges of  $x_2$  and  $x_3$  according to initial solutions in [S.2].  $x_1$  has a pre-defined discrete value from 0.2 to 15<sup>1</sup>. The three variables ( $x_1, x_2$ , and  $x_3$ ) represent the area of the reinforcement, the width of the beam, and the depth of the beam, respectively.

The second objective of RE2-3-2 is the sum of the two constraint violations:

$$f_2(\mathbf{x}) = \sum_{i=1}^2 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.6})$$

### S.1.3. RE2-4-3: Pressure vessel design problem

The first objective of the RE2-4-3 problem is to minimize the total cost (including the cost of material and the cost of forming and welding) of a cylindrical pressure vessel [S.3]:

$$f_1(\mathbf{x}) = 0.6224x_1x_3x_4 + 1.7781x_2x_3^2 + 3.1661x_1^2x_4 + 19.84x_1^2x_3, \quad (\text{S.7})$$

$$g_1(\mathbf{x}) = x_1 - 0.0193x_3 \geq 0, \quad (\text{S.8})$$

$$g_2(\mathbf{x}) = x_2 - 0.00954x_3 \geq 0, \quad (\text{S.9})$$

$$g_3(\mathbf{x}) = \pi x_3^2x_4 + \frac{4}{3}\pi x_3^3 - 1\,296\,000 \geq 0, \quad (\text{S.10})$$

where  $x_1, x_2 \in \{1, \dots, 100\}$ ,  $x_3 \in [10, 200]$ , and  $x_4 \in [10, 240]$ .  $x_1$  and  $x_2$  are integer multiples of 0.0625.  $x_1$ ,  $x_2$ ,  $x_3$ , and  $x_4$  represent the thicknesses of the shell, the head of a pressure vessel, the inner radius, and the length of the cylindrical section, respectively. We determined the ranges of  $x_2$  and  $x_3$  according to [S.3].

The second objective of RE2-4-3 is the sum of the three constraint violations:

$$f_2(\mathbf{x}) = \sum_{i=1}^3 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.11})$$

---

<sup>1</sup>For details,  $x_1 \in \{0.2, 0.31, 0.4, 0.44, 0.6, 0.62, 0.79, 0.8, 0.88, 0.93, 1, 1.2, 1.24, 1.32, 1.4, 1.55, 1.58, 1.6, 1.76, 1.8, 1.86, 2, 2.17, 2.2, 2.37, 2.4, 2.48, 2.6, 2.64, 2.79, 2.8, 3, 3.08, 3, 1, 3.16, 3.41, 3.52, 3.6, 3.72, 3.95, 3.96, 4, 4.03, 4.2, 4.34, 4.4, 4.65, 4.74, 4.8, 4.84, 5, 5.28, 5.4, 5.53, 5.72, 6, 6.16, 6.32, 6.6, 7.11, 7.2, 7.8, 7.9, 8, 8.4, 8.69, 9, 9.48, 10.27, 11, 11.06, 11.85, 12, 13, 14, 15\}$ .

*S.1.1.4. RE2-2-4: Hatch cover design problem*

The first objective of the RE2-2-4 problem is to minimize the weight of the hatch cover [S.2]:

$$f_1(\mathbf{x}) = x_1 + 120x_2, \quad (\text{S.12})$$

$$g_1(\mathbf{x}) = 1.0 - \frac{\sigma_b}{\sigma_{b,\max}} \geq 0, \quad (\text{S.13})$$

$$g_2(\mathbf{x}) = 1.0 - \frac{\tau}{\tau_{\max}} \geq 0, \quad (\text{S.14})$$

$$g_3(\mathbf{x}) = 1.0 - \frac{\delta}{\delta_{\max}} \geq 0, \quad (\text{S.15})$$

$$g_4(\mathbf{x}) = 1.0 - \frac{\sigma_b}{\sigma_k} \geq 0, \quad (\text{S.16})$$

where  $x_1 \in [0.5, 4]$  and  $x_2 \in [4, 50]$ . The ranges of the two variables were determined according to solutions reported in [S.2].  $x_1$  and  $x_2$  represent the flange thickness and the beam height of the hatch cover, respectively. The parameters are given as follows:  $\sigma_{b,\max} = 700 \text{ kg/cm}^2$ ,  $\tau_{\max} = 450 \text{ kg/cm}$ ,  $\delta_{\max} = 1.5 \text{ cm}$ ,  $\sigma_k = Ex_1^2/100 \text{ kg/cm}^2$ ,  $\sigma_b = 4500/(x_1x_2) \text{ kg/cm}^2$ ,  $\tau = 1800/x_2 \text{ kg/cm}^2$ ,  $\delta = 56.2 \times 10^4/(Ex_1x_2^2)$ , and  $E = 700\,000 \text{ kg/cm}^2$ .

The second objective of RE2-2-4 is the sum of the four constraint violations:

$$f_2(\mathbf{x}) = \sum_{i=1}^4 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.17})$$

### S.1.5. RE2-3-5: Coil compression spring design problem

The first objective of the RE2-3-5 problem is to minimize the volume of spring steel wire which is used to manufacture the spring [S.4]:

$$f_1(\mathbf{x}) = \frac{\pi^2 x_2 x_3^2 (x_1 + 2)}{4}, \quad (\text{S.18})$$

$$g_1(\mathbf{x}) = -\frac{8C_f F_{\max} x_2}{\pi x_3^3} + S \geq 0, \quad (\text{S.19})$$

$$g_2(\mathbf{x}) = -l_f + l_{\max} \geq 0, \quad (\text{S.20})$$

$$g_3(\mathbf{x}) = -3 + \frac{x_2}{x_3} \geq 0, \quad (\text{S.21})$$

$$g_4(\mathbf{x}) = -\sigma_p + \sigma_{pm} \geq 0, \quad (\text{S.22})$$

$$g_5(\mathbf{x}) = -\sigma_p - \frac{F_{\max} - F_p}{K} - 1.05(x_1 + 2)x_3 + l_f \geq 0, \quad (\text{S.23})$$

$$g_6(\mathbf{x}) = -\sigma_w + \frac{F_{\max} - F_p}{K} \geq 0, \quad (\text{S.24})$$

$$C_f = \frac{4(x_2/x_3) - 1}{4(x_2/x_3) - 4} + \frac{0.615x_3}{x_2}, \quad (\text{S.25})$$

$$K = \frac{Gx_3^4}{8x_1x_2^3}, \quad (\text{S.26})$$

$$\sigma_p = \frac{F_p}{K}, \quad (\text{S.27})$$

$$l_f = \frac{F_{\max}}{K} + 1.05(x_1 + 2)x_3, \quad (\text{S.28})$$

where  $x_1 \in \{1, \dots, 70\}$ ,  $x_2 \in [0.6, 30]$ , and  $x_3$  has a predefined discrete value from 0.009 to 0.5.<sup>2</sup>  $x_1, x_2$ , and  $x_3$  indicate the number of spring coils, the outside diameter of the spring, and the spring wire diameter, respectively. The parameters are given as follows:  $F_{\max} = 1\,000\text{lb}$ ,  $S = 189\,000\text{psi}$ ,  $l_{\max} = 14\text{inch}$ ,  $d_{\min} = 0.2\text{inch}$ ,  $D_{\max} = 3\text{inch}$ ,  $F_p = 300\text{lb}$ ,  $\sigma_{pm} = 6\text{ inch}$ ,  $\sigma_w = 1.25\text{inch}$ ,  $G = 11.5 \times 10^6$ .

The second objective of RE2-3-5 is the sum of the six constraint violations:

$$f_2(\mathbf{x}) = \sum_{i=1}^6 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.29})$$

---

<sup>2</sup>For details,  $x_3 \in \{0.009, 0.0095, 0.0104, 0.0118, 0.0128, 0.0132, 0.014, 0.015, 0.0162, 0.0173, 0.018, 0.02, 0.023, 0.025, 0.028, 0.032, 0.035, 0.041, 0.047, 0.054, 0.063, 0.072, 0.08, 0.092, 0.105, 0.12, 0.135, 0.148, 0.162, 0.177, 0.192, 0.207, 0.225, 0.244, 0.263, 0.283, 0.307, 0.331, 0.362, 0.394, 0.4375, 0.5\}$ .

*S.1.6. RE3-3-1: Two bar truss design problem*

The first and second objectives of the RE3-3-1 problem are to minimize the structural weight ( $f_1$ ) and resultant displacement of join ( $f_2$ ) of the two bar truss [S.5]:

$$f_1(\mathbf{x}) = x_1\sqrt{16 + x_3^2} + x_2\sqrt{1 + x_3^2}, \quad (\text{S.30})$$

$$f_2(\mathbf{x}) = \frac{20\sqrt{16 + x_3^2}}{x_3x_1}, \quad (\text{S.31})$$

$$g_1(\mathbf{x}) = 0.1 - f_1(\mathbf{x}) \geq 0, \quad (\text{S.32})$$

$$g_2(\mathbf{x}) = 10^5 - f_2(\mathbf{x}) \geq 0, \quad (\text{S.33})$$

$$g_3(\mathbf{x}) = 10^5 - \frac{80\sqrt{1 + x_3^2}}{x_3x_2} \geq 0, \quad (\text{S.34})$$

where  $x_1, x_2 \in [10^{-5}, 100]^3$  and  $x_3 \in [1, 3]$ .  $x_1$  and  $x_2$  indicate the length of the two bars.  $x_3$  represents the vertical distance from the second bar.

The third objective of RE3-3-1 is the sum of the three constraint violations:

$$f_3(\mathbf{x}) = \sum_{i=1}^3 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.35})$$

---

<sup>3</sup>The original range of  $x_1$  and  $x_2$  is as follows:  $x_1, x_2 > 0$ . Thus,  $x_1$  and  $x_2$  can be any non-negative values. To define this problem as a bound constrained problem, we set the upper bound and the lower bound.

*S.1.7. RE3-4-2: Welded beam design problem*

The first and second objectives of the RE3-4-2 problem are to minimize cost ( $f_1$ ) and end deflection ( $f_2$ ) of a welded beam [S.6]:

$$f_1(\mathbf{x}) = 1.10471x_1^2x_2 + 0.04811x_3x_4(14 + x_2), \quad (\text{S.36})$$

$$f_2(\mathbf{x}) = \frac{4PL^3}{Ex_4x_3^3}, \quad (\text{S.37})$$

$$g_1(\mathbf{x}) = \tau_{\max} - \tau(\mathbf{x}) \geq 0, \quad (\text{S.38})$$

$$g_2(\mathbf{x}) = \sigma_{\max} - \sigma(\mathbf{x}) \geq 0, \quad (\text{S.39})$$

$$g_3(\mathbf{x}) = x_4 - x_1 \geq 0, \quad (\text{S.40})$$

$$g_4(\mathbf{x}) = P_C(\mathbf{x}) - P \geq 0, \quad (\text{S.41})$$

$$\tau(\mathbf{x}) = \sqrt{(\tau')^2 + \frac{2\tau'\tau''x_2}{2R} + (\tau'')^2}, \quad (\text{S.42})$$

$$\tau' = \frac{P}{\sqrt{2}x_1x_2}, \quad (\text{S.43})$$

$$\tau'' = \frac{MR}{J}, \quad (\text{S.44})$$

$$M = P \left( L + \frac{x_2}{2} \right), \quad (\text{S.45})$$

$$R = \sqrt{\frac{x_2^2}{4} + \left( \frac{x_1 + x_3}{2} \right)^2}, \quad (\text{S.46})$$

$$J = 2 \left( \sqrt{2}x_1x_2 \left( \frac{x_2^2}{12} + \left( \frac{x_1 + x_3}{2} \right)^2 \right) \right), \quad (\text{S.47})$$

$$\sigma(\mathbf{x}) = \frac{6PL}{x_4x_3^2}, \quad (\text{S.48})$$

$$P_C(\mathbf{x}) = \frac{4.013E\sqrt{x_3^2x_4^6/36}}{L^2} \left( 1 - \frac{x_3}{2L}\sqrt{\frac{E}{4G}} \right), \quad (\text{S.49})$$

where  $x_1, x_4 \in [0.125, 5]$  and  $x_2, x_3 \in [0.1, 10]$ . The four variables adjust the size of the beam. The parameters are given as follows:  $P = 6\,000\text{lb}$ ,  $L = 14\text{in}$ ,  $E = 30 \times 10^6\text{psi}$ ,  $G = 12 \times 10^6\text{psi}$ ,  $\tau_{\max} = 13\,600\text{psi}$ , and  $\sigma_{\max} = 30\,000\text{psi}$ .

The third objective of RE3-4-2 is the sum of the four constraint violations:

$$f_3(\mathbf{x}) = \sum_{i=1}^4 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.50})$$

### S.1.8. RE3-4-3: Disc brake design problem

The first and second objectives of the RE3-4-3 problem are to minimize the mass of the brake ( $f_1$ ) and the minimum stopping time ( $f_2$ ) of a disc brake [S.6]:

$$f_1(\mathbf{x}) = 4.9 \times 10^{-5}(x_2^2 - x_1^2)(x_4 - 1), \quad (\text{S.51})$$

$$f_2(\mathbf{x}) = 9.82 \times 10^6 \left( \frac{x_2^2 - x_1^2}{x_3 x_4 (x_2^3 - x_1^3)} \right), \quad (\text{S.52})$$

$$g_1(\mathbf{x}) = (x_2 - x_1) - 20 \geq 0, \quad (\text{S.53})$$

$$g_2(\mathbf{x}) = 0.4 - \frac{x_3}{3.14(x_2^2 - x_1^2)} \geq 0, \quad (\text{S.54})$$

$$g_3(\mathbf{x}) = 1 - \frac{2.22 \times 10^{-3} x_3 (x_2^3 - x_1^3)}{(x_2^2 - x_1^2)^2} \geq 0, \quad (\text{S.55})$$

$$g_4(\mathbf{x}) = \frac{2.66 \times 10^{-2} x_3 x_4 (x_2^3 - x_1^3)}{(x_2^2 - x_1^2)} - 900 \geq 0, \quad (\text{S.56})$$

where  $x_1 \in [55, 80]$ ,  $x_2 \in [75, 110]$ ,  $x_3 \in [1000, 3000]$ ,  $x_4 \in [11, 20]$ <sup>4</sup>. The four variables ( $x_1$ ,  $x_2$ ,  $x_3$ , and  $x_4$ ) represent the inner radius of the discs, the outer radius of the discs, the engaging force, and the number of friction surfaces, respectively.

The third objective of RE3-4-3 is the sum of the four constraint violations:

$$f_3(\mathbf{x}) = \sum_{i=1}^4 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.57})$$

### S.1.9. RE3-5-4: The vehicle crashworthiness design problem

The first, second, and third objectives of the RE3-5-4 problem are to minimize the weight ( $f_1$ ), acceleration characteristics ( $f_2$ ), and toe-board instruction ( $f_3$ ) of the vehicle design [S.7]:

$$\begin{aligned} f_1(\mathbf{x}) = & 1640.2823 + 2.3573285x_1 + 2.3220035x_2 \\ & + 4.5688768x_3 + 7.7213633x_4 \\ & + 4.4559504x_5, \end{aligned} \quad (\text{S.58})$$

$$\begin{aligned} f_2(\mathbf{x}) = & 6.5856 + 1.15x_1 - 1.0427x_2 + 0.9738x_3 \\ & + 0.8364x_4 - 0.3695x_1x_4 + 0.0861x_1x_5 \\ & + 0.3628x_2x_4 - 0.1106x_1^2 - 0.3437x_3^2 \\ & + 0.1764x_4^2, \end{aligned} \quad (\text{S.59})$$

---

<sup>4</sup>The original range for  $x_4$  is  $[2, 20]$ , but  $x_4$  has a constraint such that  $x_4 \geq 11$ .

$$\begin{aligned}
f_3(\mathbf{x}) = & -0.0551 + 0.0181x_1 + 0.1024x_2 \\
& + 0.0421x_3 - 0.0073x_1x_2 + 0.024x_2x_3 \\
& - 0.0118x_2x_4 - 0.0204x_3x_4 - 0.008x_3x_5 \\
& - 0.0241x_2^2 + 0.0109x_4^2,
\end{aligned} \tag{S.60}$$

where  $x_i \in [1, 3]$  for each  $i \in \{1, \dots, 5\}$ . The five variables specify the thickness of five reinforced members around the frontal structure of the vehicle. The parameters in (S.58)–(S.60) were obtained by the response surface method using data sampled from a simulation of a full-scale vehicle model.

*S.1.10. RE3-7-5: The speed reducer design problem*

The first and second objectives of the RE3-7-5 problem are to minimize the volume ( $f_1$ ) and the stress in one of the two gear shafts ( $f_2$ ) of a speed reducer [S.8]:

$$\begin{aligned}
f_1(\mathbf{x}) = & 0.7854x_1x_2^2 \left( \frac{10x_3^2}{3} + 14.933x_3 - 43.0934 \right) \\
& - 1.508x_1(x_6^2 + x_7^2) + 7.477(x_6^3 + x_7^3) \\
& + 0.7854(x_4x_6^2 + x_5x_7^2),
\end{aligned} \tag{S.61}$$

$$f_2(\mathbf{x}) = \frac{\sqrt{(745x_4/x_2x_3)^2 + 1.69 \times 10^7}}{0.1x_6^3}, \tag{S.62}$$

$$g_1(\mathbf{x}) = \frac{1}{27} - \frac{1}{x_1x_2^2x_3} \geq 0, \tag{S.63}$$

$$g_2(\mathbf{x}) = \frac{1}{397.5} - \frac{1}{x_1x_2^2x_3^2} \geq 0, \tag{S.64}$$

$$g_3(\mathbf{x}) = \frac{1}{1.93} - \frac{x_4^3}{x_2x_3x_6^4} \geq 0, \tag{S.65}$$

$$g_4(\mathbf{x}) = \frac{1}{1.93} - \frac{x_5^3}{x_2x_3x_7^4} \geq 0, \tag{S.66}$$

$$g_5(\mathbf{x}) = 40 - x_2x_3 \geq 0, \tag{S.67}$$

$$g_6(\mathbf{x}) = 12 - \frac{x_1}{x_2} \geq 0, \tag{S.68}$$

$$g_7(\mathbf{x}) = -5 + \frac{x_1}{x_2} \geq 0, \tag{S.69}$$

$$g_8(\mathbf{x}) = -1.9 + x_4 - 1.5x_6 \geq 0, \tag{S.70}$$

$$g_9(\mathbf{x}) = -1.9 + x_5 - 1.1x_7 \geq 0, \tag{S.71}$$

$$g_{10}(\mathbf{x}) = 1300 - f_2(\mathbf{x}) \geq 0, \tag{S.72}$$

$$g_{11}(\mathbf{x}) = 1100 - \frac{\sqrt{(745x_5/x_2x_3)^2 + 1.575 \times 10^8}}{0.1x_7^3} \geq 0, \tag{S.73}$$



where  $x_1 \in [2.6, 3.6]$ ,  $x_2 \in [0.7, 0.8]$ ,  $x_3 \in \{17, \dots, 28\}$ ,  $x_4 \in [7.3, 8.3]$ ,  $x_5 \in [7.3, 8.3]$ ,  $x_6 \in [2.9, 3.9]$ , and  $x_7 \in [5, 5.5]$ .  $x_3$  is an integer variable. The seven variables represent the gear face width ( $x_1$ ), the teeth module ( $x_2$ ), the number of teeth of a pinion ( $x_3$ ), the distance between bearings on the first shaft ( $x_4$ ), the distance between bearings on the second shaft ( $x_5$ ), the diameter of the first shaft ( $x_6$ ), and the diameter of the second shaft ( $x_7$ ).

The third objective of RE3-7-5 is the sum of the 11 constraint violations:

$$f_3(\mathbf{x}) = \sum_{i=1}^{11} \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.74})$$

#### *S.1.11. RE3-4-6: Gear train design problem*

The first and second objectives of this problem are to minimize the error between the realized gear ration and the given required gear ration ( $f_1$ ) and the maximum size of the four gears ( $f_2$ ) [S.9]:

$$f_1(\mathbf{x}) = \left| 6.931 - \frac{x_3}{x_1} \frac{x_4}{x_2} \right|, \quad (\text{S.75})$$

$$f_2(\mathbf{x}) = \max\{x_1, x_2, x_3, x_4\}, \quad (\text{S.76})$$

$$g_1(\mathbf{x}) = 0.5 - \frac{f_1(\mathbf{x})}{6.931} \geq 0, \quad (\text{S.77})$$

where the four variables must be integer, and  $x_1, x_2, x_3, x_4 \in \{12, \dots, 60\}$ . The four variables represent the number of teeth in each of the four gears.

The third objective of RE3-4-6 is the constraint violation of  $g_1$ :

$$f_3(\mathbf{x}) = \max\{-g_1(\mathbf{x}), 0\}. \quad (\text{S.78})$$

#### *S.1.12. RE3-4-7: Rocket injector design problem*

The original RE3-4-7 problem is a four-objective problem [S.10]. However, as in [S.11, 12], we handle RE3-4-7 as a three-objective problem. The first, second, and third objectives of the RE3-4-7 problem are to minimize the maximum temperature of the injector face ( $f_1$ ), the distance from the inlet ( $f_2$ ), and the

maximum temperature on the post tip ( $f_3$ ) [S.11]:

$$\begin{aligned} f_1(\mathbf{x}) = & 0.692 + (0.477x_1) - (0.687x_2) - (0.080x_3) - (0.0650x_4) - (0.167x_1x_1) \\ & - (0.0129x_2x_1) + (0.0796x_2x_2) - (0.0634x_3x_1) - (0.0257x_3x_2) \\ & + (0.0877x_3x_3) - (0.0521x_4x_1) + (0.00156x_4x_2) + (0.00198x_4x_3) \\ & + (0.0184x_4x_4) \end{aligned} \quad (\text{S.79})$$

$$\begin{aligned} f_2(\mathbf{x}) = & 0.153 - (0.322x_1) + (0.396x_2) + (0.424x_3) + (0.0226x_4) \\ & + (0.175x_1x_1) + (0.0185x_2x_1) - (0.0701x_2x_2) - (0.251x_3x_1) \\ & + (0.179x_3x_2) + (0.0150x_3x_3) + (0.0134x_4x_1) + (0.0296x_4x_2) \\ & + (0.0752x_4x_3) + (0.0192x_4x_4) \end{aligned} \quad (\text{S.80})$$

$$\begin{aligned} f_3(\mathbf{x}) = & 0.370 - (0.205x_1) + (0.0307x_2) + (0.108x_3) + (1.019x_4) \\ & - (0.135x_1x_1) + (0.0141x_2x_1) + (0.0998x_2x_2) + (0.208x_3x_1) \\ & - (0.0301x_3x_2) - (0.226x_3x_3) + (0.353x_4x_1) - (0.0497x_4x_3) \\ & - (0.423x_4x_4) + (0.202x_2x_1x_1) - (0.281x_3x_1x_1) - (0.342x_2x_2x_1) \\ & - (0.245x_2x_2x_3) + (0.281x_3x_3x_2) - (0.184x_4x_4x_1) - (0.281x_2x_1x_3) \end{aligned} \quad (\text{S.81})$$

where  $x_i \in [0, 1]$  for each  $i \in \{1, \dots, 4\}$ .  $x_1$  is the hydrogen flow angle ( $\alpha$ ).  $x_2$  is the hydrogen area ( $\Delta\text{HA}$ ).  $x_3$  is the oxygen area ( $\Delta\text{OA}$ ).  $x_4$  is the oxidizer post tip thickness (OPTT). The parameters in (S.79)–(S.81) were obtained by the response surface method using data obtained by a CFD-based simulation.

#### S.1.13. RE4-7-1: Car side impact design problem

The car side impact design problem, which was originally used in [S.13, 14], is the problem of minimizing the weight of the car ( $f_1$ ), the pubic force experienced by a passenger ( $f_2$ ), and the average velocity of the V-pillar responsible for withstanding the impact load ( $f_3$ ) [S.15]. Unlike the original problem, four stochastic parameters are excluded in this version.

The first, second, and third objectives of the RE4-7-1 problem are given as

follows:

$$\begin{aligned} f_1(\mathbf{x}) = & 1.98 + 4.9x_1 + 6.67x_2 + 6.98x_3 \\ & + 4.01x_4 + 1.78x_5 + 10^{-5}x_6 \\ & + 2.73x_7, \end{aligned} \quad (\text{S.82})$$

$$f_2(\mathbf{x}) = 4.72 - 0.5x_4 - 0.19x_2x_3, \quad (\text{S.83})$$

$$f_3(\mathbf{x}) = 0.5(V_{\text{MBP}}(\mathbf{x}) + V_{\text{FD}}(\mathbf{x})), \quad (\text{S.84})$$

$$\begin{aligned} g_1(\mathbf{x}) = & 1 - 1.16 + 0.3717x_2x_4 \\ & + 0.0092928x_3 \geq 0, \end{aligned} \quad (\text{S.85})$$

$$\begin{aligned} g_2(\mathbf{x}) = & 0.32 - 0.261 + 0.0159x_1x_2 + 0.06486x_1 \\ & + 0.019x_2x_7 - 0.0144x_3x_5 \\ & - 0.0154464x_6 \geq 0, \end{aligned} \quad (\text{S.86})$$

$$\begin{aligned} g_3(\mathbf{x}) = & 0.32 - 0.214 - 0.00817x_5 + 0.045195x_1 \\ & + 0.0135168x_1 - 0.03099x_2x_6 \\ & + 0.018x_2x_7 - 0.007176x_3 \\ & - 0.023232x_3 + 0.00364x_5x_6 \\ & + 0.018x_2^2 \geq 0, \end{aligned} \quad (\text{S.87})$$

$$\begin{aligned} g_4(\mathbf{x}) = & 0.32 - 0.74 + 0.61x_2 + 0.031296x_3 \\ & + 0.031872x_7 - 0.227x_2^2 \geq 0, \end{aligned} \quad (\text{S.88})$$

$$\begin{aligned} g_5(\mathbf{x}) = & 32 - 28.98 - 3.818x_3 + 4.2x_1x_2 \\ & - 1.27296x_6 + 2.68065x_7 \geq 0, \end{aligned} \quad (\text{S.89})$$

$$\begin{aligned} g_6(\mathbf{x}) = & 32 - 33.86 - 2.95x_3 + 5.057x_1x_2 \\ & + 3.795x_2 + 3.4431x_7 - 1.45728 \geq 0, \end{aligned} \quad (\text{S.90})$$

$$g_7(\mathbf{x}) = 32 - 46.36 + 9.9x_2 + 4.4505x_1 \geq 0, \quad (\text{S.91})$$

$$g_8(\mathbf{x}) = 4 - f_2(\mathbf{x}) \geq 0, \quad (\text{S.92})$$

$$g_9(\mathbf{x}) = 9.9 - V_{\text{MBP}}(\mathbf{x}) \geq 0, \quad (\text{S.93})$$

$$g_{10}(\mathbf{x}) = 15.7 - V_{\text{FD}}(\mathbf{x}) \geq 0, \quad (\text{S.94})$$

$$V_{\text{MBP}}(\mathbf{x}) = 10.58 - 0.674x_1x_2 - 0.67275x_2, \quad (\text{S.95})$$

$$V_{\text{FD}}(\mathbf{x}) = 16.45 - 0.489x_3x_7 - 0.843x_5x_6, \quad (\text{S.96})$$

where  $x_1 \in [0.5, 1.5]$ ,  $x_2 \in [0.45, 1.35]$ ,  $x_3 \in [0.5, 1.5]$ ,  $x_4 \in [0.5, 1.5]$ ,  $x_5 \in [0.875, 2.625]$ ,  $x_6 \in [0.4, 1.2]$ , and  $x_7 \in [0.4, 1.2]$ . The parameters in (S.82)–(S.96) were obtained by the response surface method similar to the RE3-5-4 problem.

The fourth objective of RE4-7-1 is the sum of the 10 constraint violations:

$$f_4(\mathbf{x}) = \sum_{i=1}^{10} \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.97})$$

*S.1.14. RE4-6-2: Conceptual marine design problem*

The first, second, and third objectives of the RE4-6-2 problem are to minimize the transportation cost ( $f_1$ ), the light ship weight ( $f_2$ ), and the annual cargo transport capacity ( $f_3$ ) [S.16]:

$$f_1(\mathbf{x}) = \frac{\text{annual\_costs}}{\text{annual\_cargo}}, \quad (\text{S.98})$$

$$\begin{aligned} f_2(\mathbf{x}) &= \text{light\_ship\_weight} \\ &= W_s + W_o + W_m, \end{aligned} \quad (\text{S.99})$$

$$\begin{aligned} f_3(\mathbf{x}) &= \text{annual\_cargo} \\ &= - \text{cargo\_DWT} \times \text{RTPA}, \end{aligned} \quad (\text{S.100})$$

$$g_1(\mathbf{x}) = \frac{L}{B} - 6 \geq 0, \quad (\text{S.101})$$

$$g_2(\mathbf{x}) = 15 - \frac{L}{D} \geq 0, \quad (\text{S.102})$$

$$g_3(\mathbf{x}) = 19 - \frac{L}{T} \geq 0, \quad (\text{S.103})$$

$$g_4(\mathbf{x}) = 0.45\text{DWT}^{0.31} - T \geq 0, \quad (\text{S.104})$$

$$g_5(\mathbf{x}) = 0.7D + 0.7 - T \geq 0, \quad (\text{S.105})$$

$$g_6(\mathbf{x}) = \text{DWT} - 3\,000 \geq 0, \quad (\text{S.106})$$

$$g_7(\mathbf{x}) = 500\,000 - \text{DWT} \geq 0, \quad (\text{S.107})$$

$$g_8(\mathbf{x}) = 0.32 - F_n \geq 0, \quad (\text{S.108})$$

$$\begin{aligned} g_9(\mathbf{x}) &= KB + BM_T - KG \\ &\quad - 0.07B \geq 0, \end{aligned} \quad (\text{S.109})$$

$$\begin{aligned} \text{annual\_costs} &= \text{capital\_costs} \\ &\quad + \text{running\_costs} \\ &\quad + \text{voyage\_costs}, \end{aligned} \quad (\text{S.110})$$

$$\text{capital\_costs} = 0.2\text{ship\_cost}, \quad (\text{S.111})$$

$$\begin{aligned} \text{ship\_cost} &= 1.3(2\,000W_s^{0.85} + 3\,500W_o \\ &\quad + 2\,400P^{0.8}), \end{aligned} \quad (\text{S.112})$$

$$\begin{aligned}\text{steel\_weight} &= W_s \\ &= 0.034 L^{1.7} B^{0.7} D^{0.4} C_B^{0.5},\end{aligned}\quad (\text{S.113})$$

$$\begin{aligned}\text{outfit\_weight} &= W_o \\ &= 1.0 L^{0.8} B^{0.6} D^{0.3} C_B^{0.1},\end{aligned}\quad (\text{S.114})$$

$$\text{machinery\_weight} = W_m = 0.17 P^{0.9}, \quad (\text{S.115})$$

$$\text{displacement} = 1.025 L B T C_B, \quad (\text{S.116})$$

$$\begin{aligned}\text{power} &= P \\ &= \frac{\text{displacement}^{2/3} V_k^3}{a + b F_n},\end{aligned}\quad (\text{S.117})$$

$$\text{Froudenumber} = F_n = \frac{V}{(gL)^{0.5}}, \quad (\text{S.118})$$

$$V = 0.5144 V_k, \quad (\text{S.119})$$

$$g = 9.8065, \quad (\text{S.120})$$

$$\text{AC} = a + b F_n, \quad (\text{S.121})$$

$$\begin{aligned}a &= 4977.06 C_B^2 \\ &\quad - 8105.61 C_B \\ &\quad + 4456.51,\end{aligned}\quad (\text{S.122})$$

$$\begin{aligned}b &= -10847.2 C_B^2 \\ &\quad + 12817 C_B \\ &\quad - 6960.32,\end{aligned}\quad (\text{S.123})$$

$$\text{running\_costs} = 40\,000 \text{DWT}^{0.3}, \quad (\text{S.124})$$

$$\begin{aligned}\text{deadweight} &= \text{DWT} = \text{displacement} \\ &\quad - \text{light\_ship},\end{aligned}\quad (\text{S.125})$$

$$\begin{aligned}\text{voyage\_costs} &= (\text{fuel\_cost} \\ &\quad + \text{port\_cost}) \text{RTPA},\end{aligned}\quad (\text{S.126})$$

$$\begin{aligned}\text{fuel\_cost} &= 1.05 \text{ daily\_consumption} \\ &\quad \times \text{sea\_days} \times \text{fuel\_price},\end{aligned}\quad (\text{S.127})$$

$$\text{daily\_consumption} = \frac{0.19 P \times 24}{1\,000} + 0.2, \quad (\text{S.128})$$

$$\text{sea\_days} = \frac{\text{round\_trip\_miles}}{24} V_k, \quad (\text{S.129})$$

$$\text{round\_trip\_miles} = 5\,000, \quad (\text{S.130})$$

$$\text{fuel\_price} = 100, \quad (\text{S.131})$$

$$\text{port\_cost} = 6.3 \text{DWT}^{0.8}, \quad (\text{S.132})$$

$$\begin{aligned}\text{round\_trips\_per\_year} &= \text{RTPA} \\ &= \frac{350}{\text{sea\_days} + \text{port\_days}},\end{aligned}\quad (\text{S.133})$$

$$\text{port\_days} = 2 \left( \frac{\text{cargo\_DWT}}{\text{handling\_rate}} + 0.5 \right), \quad (\text{S.134})$$

$$\begin{aligned} \text{cargo\_deadweight} &= \text{cargo\_DWT} \\ &= \text{DWT} - \text{fuel\_carried} \\ &\quad - \text{miscellaneous\_DWT}, \end{aligned} \quad (\text{S.135})$$

$$\begin{aligned} \text{fuel\_carried} &= \text{daily\_consumption} \\ &\quad \times (\text{sea\_days} + 5), \end{aligned} \quad (\text{S.136})$$

$$\text{miscellaneous\_DWT} = 2\text{DWT}^{0.5}, \quad (\text{S.137})$$

$$\text{handling\_rate} = 8000, \quad (\text{S.138})$$

$$\text{vertical\_center\_of\_buoyancy} = KB = 0.53T, \quad (\text{S.139})$$

$$\begin{aligned} \text{metacentric\_radius} &= BM_T \\ &= \frac{(0.085C_B - 0.002)B^2}{TC_B}, \end{aligned} \quad (\text{S.140})$$

$$\text{vertical\_center\_of\_gravity} = KG = 1 + 0.52D, \quad (\text{S.141})$$

where  $L, B, D, T, V_k$ , and  $C_B$  correspond to six decision variables ( $x_1, x_2, x_3, x_4, x_5$ , and  $x_6$ ), respectively. The range of the six variables are as follows:  $L \in [150, 274.32]$ ,  $B \in [20, 32.31]$ ,  $D \in [13, 25]$ ,  $T \in [10, 11.71]$ ,  $V_k \in [14, 18]$ , and  $C_B \in [0.63, 0.75]$ . We selected the range of the six variables according to [S.17].  $L, B, D, T, V_k$ , and  $C_B$  indicate the values of length, beam, depth, draft, speed, and block coefficients, respectively. Although  $f_3$  is to be maximized in the original definition, it is modified for a minimization problem.

The fourth objective of RE4-6-2 is the sum of the nine constraint violations:

$$f_4(\mathbf{x}) = \sum_{i=1}^9 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.142})$$

#### *S.1.15. RE6-3-1: Water resource planning problem*

The five objectives of the RE6-3-1 problem are to minimize the drainage network cost ( $f_1$ ), the storage facility cost ( $f_2$ ), the treatment facility cost ( $f_3$ ), the expected flood damage cost ( $f_4$ ), and the expected economic loss due to

flood ( $f_5$ ) of a water resource planning [S.18]:

$$f_1(\mathbf{x}) = 106780.37(x_2 + x_3) + 61704.67, \quad (\text{S.143})$$

$$f_2(\mathbf{x}) = 3000x_1, \quad (\text{S.144})$$

$$f_3(\mathbf{x}) = \frac{305700 \times 2289x_2}{(0.06 \times 2289)^{0.65}}, \quad (\text{S.145})$$

$$f_4(\mathbf{x}) = 250 \times 2289 \exp(-39.75x_2 + 9.9x_3 + 2.74), \quad (\text{S.146})$$

$$f_5(\mathbf{x}) = 25 \left( \frac{1.39}{x_1x_2} + 4940x_3 - 80 \right), \quad (\text{S.147})$$

$$g_1(\mathbf{x}) = 1 - \frac{0.00139}{x_1x_2} - 4.94x_3 + 0.08 \geq 0, \quad (\text{S.148})$$

$$g_2(\mathbf{x}) = 1 - \frac{0.000306}{x_1x_2} - 1.082x_3 + 0.0986 \geq 0, \quad (\text{S.149})$$

$$g_3(\mathbf{x}) = 50000 - \frac{12.307}{x_1x_2} - 49408.24x_3 - 4051.02 \geq 0, \quad (\text{S.150})$$

$$g_4(\mathbf{x}) = 16000 - \frac{2.098}{x_1x_2} - 8046.33x_3 + 696.71 \geq 0, \quad (\text{S.151})$$

$$g_5(\mathbf{x}) = 10000 - \frac{2.138}{x_1x_2} - 7883.39x_3 + 705.04 \geq 0, \quad (\text{S.152})$$

$$g_6(\mathbf{x}) = 2000 - 0.417(x_1x_2) - 1721.26x_3 + 136.54 \geq 0, \quad (\text{S.153})$$

$$g_7(\mathbf{x}) = 550 - \frac{0.164}{x_1x_2} - 631.13x_3 + 54.48 \geq 0, \quad (\text{S.154})$$

where  $x_1 \in [0.01, 0.45]$ ,  $x_2 \in [0.01, 0.1]$ , and  $x_3 \in [0.01, 0.1]$ .  $x_1$ ,  $x_2$ , and  $x_3$  represent the local detention storage capacity, the maximum treatment rate, and the maximum allowable overflow rate, respectively.

The sixth objective of RE6-3-1 is the sum of the seven constraint violations:

$$f_6(\mathbf{x}) = \sum_{i=1}^7 \max\{-g_i(\mathbf{x}), 0\}. \quad (\text{S.155})$$

#### S.1.16. RE9-7-1: The car cab design

This is an alternative version of the RE4-7-1 problem [S.19]. The RE9-7-1 problem is closer than RE4-7-1 to the original problem [S.13]. The first objective

of RE9-7-1 is to minimize the weight of the car ( $f_1$ ) as follows (in the following formulations, three constraint functions are combined in a similar manner to [S.20]):

$$\begin{aligned} f_1(\mathbf{x}) = & 1.98 + 4.9x_1 + 6.67x_2 + 6.98x_3 \\ & + 4.01x_4 + 1.78x_5 + 0.00001x_6 \\ & + 2.73x_7, \end{aligned} \tag{S.156}$$

$$\begin{aligned} g_1(\mathbf{x}) = & 1 - (1.16 - 0.3717x_2x_4 \\ & - 0.00931x_2x_{10} - 0.484x_3x_9 \\ & + 0.01343x_6x_{10}) \geq 0, \end{aligned} \tag{S.157}$$

$$\begin{aligned} g_2(\mathbf{x}) = & 0.32 - (0.261 - 0.0159x_1x_2 \\ & - 0.188x_1x_8 - 0.019x_2x_7 \\ & + 0.0144x_3x_5 + 0.87570001x_5x_{10} \\ & + 0.08045x_6x_9 + 0.00139x_8x_{11} \\ & + 0.00001575x_{10}x_{11}) \geq 0, \end{aligned} \tag{S.158}$$

$$\begin{aligned} g_3(\mathbf{x}) = & 0.32 - (0.214 + 0.00817x_5 \\ & - 0.131x_1x_8 - 0.0704x_1x_9 \\ & + 0.03099x_2x_6 - 0.018x_2x_7 \\ & + 0.0208x_3x_8 + 0.121x_3x_9 \\ & - 0.00364x_5x_6 + 0.0007715x_5x_{10} \\ & - 0.0005354x_6x_{10} + 0.00121x_8x_{11} \\ & + 0.00184x_9x_{10} - 0.018x_2x_2) \geq 0, \end{aligned} \tag{S.159}$$

$$\begin{aligned} g_4(\mathbf{x}) = & 0.32 - (0.74 - 0.61x_2 - 0.163x_3x_8 \\ & + 0.001232x_3x_{10} - 0.166x_7x_9 \\ & + 0.227x_2x_2) \geq 0, \end{aligned} \tag{S.160}$$

$$g_5(\mathbf{x}) = 32 - \left( \frac{\text{URD} \times \text{MRD} \times \text{LRD}}{3} \right) \geq 0, \tag{S.161}$$

$$\begin{aligned} g_6(\mathbf{x}) = & 32 - (4.72 - 0.5x_4 - 0.19x_2x_3 \\ & - 0.0122x_4x_{10} + 0.009325x_6x_{10} \\ & + 0.000191x_{11}x_{11}) \geq 0, \end{aligned} \tag{S.162}$$

$$\begin{aligned} g_7(\mathbf{x}) = & 4 - (10.58 - 0.674x_1x_2 - 1.95x_2x_8 \\ & + 0.02054x_3x_{10} - 0.0198x_4x_{10} \\ & + 0.028x_6x_{10}) \geq 0, \end{aligned} \tag{S.163}$$

$$\begin{aligned} g_8(\mathbf{x}) = & 9.9 - (16.45 - 0.489x_3x_7 - 0.843x_5x_6 \\ & + 0.0432x_9x_{10} - 0.0556x_9x_{11} \\ & - 0.000786x_{11}x_{11}) \geq 0, \end{aligned} \tag{S.164}$$



$$\begin{aligned}
\text{upper\_rib\_deflection} &= \text{URD} \\
&= 28.98 + 3.818x_3 - 4.2x_1x_2 \\
&\quad + 0.0207x_5x_{10} + 6.63x_6x_9 \\
&\quad - 7.77x_7x_8 + 0.32x_9x_{10}, \tag{S.165}
\end{aligned}$$

$$\begin{aligned}
\text{middle\_rib\_deflection} &= \text{MRD} \\
&= 33.86 + 2.95x_3 \\
&\quad + 0.1792x_{10} - 5.057x_1x_2 \\
&\quad - 11x_2x_8 - 0.0215x_5x_{10} \\
&\quad - 9.98x_7x_8 + 22x_8x_9, \tag{S.166}
\end{aligned}$$

$$\begin{aligned}
\text{lower\_rib\_deflection} &= \text{LRD} \\
&= 46.36 - 9.9x_2 - 12.9x_1x_8 \\
&\quad + 0.1107x_3x_{10}, \tag{S.167}
\end{aligned}$$

where  $x_1 \in [0.5, 1.5]$ ,  $x_2 \in [0.45, 1.35]$ ,  $x_3 \in [0.5, 1.5]$ ,  $x_4 \in [0.5, 1.5]$ ,  $x_5 \in [0.875, 2.625]$ ,  $x_6 \in [0.4, 1.2]$ ,  $x_7 \in [0.4, 1.2]$ . The seven variables indicate the thickness of the following parts: B-Pillar inner ( $x_1$ ), B-Pillar reinforcement ( $x_2$ ), floor side inner ( $x_3$ ), cross members ( $x_4$ ), door beam ( $x_5$ ), the door belt-line reinforcement ( $x_6$ ), and roof rail ( $x_7$ ). The remaining four variables ( $x_8$ ,  $x_9$ ,  $x_{10}$ , and  $x_{11}$ ) are stochastic parameters, which represent the material of B-Pillar inner ( $x_8$ ), the material of floor side inner ( $x_9$ ), the barrier height ( $x_{10}$ ), and the barrier hitting position ( $x_{11}$ ).

Each of the other eight objectives ( $f_2, \dots, f_9$ ) of RE9-7-1 corresponds to each of the eight constraint violations:

$$f_2(\mathbf{x}) = \max\{g_2(\mathbf{x}), 0\}, \tag{S.168}$$

$$f_3(\mathbf{x}) = \max\{g_3(\mathbf{x}), 0\}, \tag{S.169}$$

$$f_4(\mathbf{x}) = \max\{g_4(\mathbf{x}), 0\}, \tag{S.170}$$

$$f_5(\mathbf{x}) = \max\{g_5(\mathbf{x}), 0\}, \tag{S.171}$$

$$f_6(\mathbf{x}) = \max\{g_6(\mathbf{x}), 0\}, \tag{S.172}$$

$$f_7(\mathbf{x}) = \max\{g_7(\mathbf{x}), 0\}, \tag{S.173}$$

$$f_8(\mathbf{x}) = \max\{g_8(\mathbf{x}), 0\}, \tag{S.174}$$

$$f_9(\mathbf{x}) = \max\{g_9(\mathbf{x}), 0\}. \tag{S.175}$$

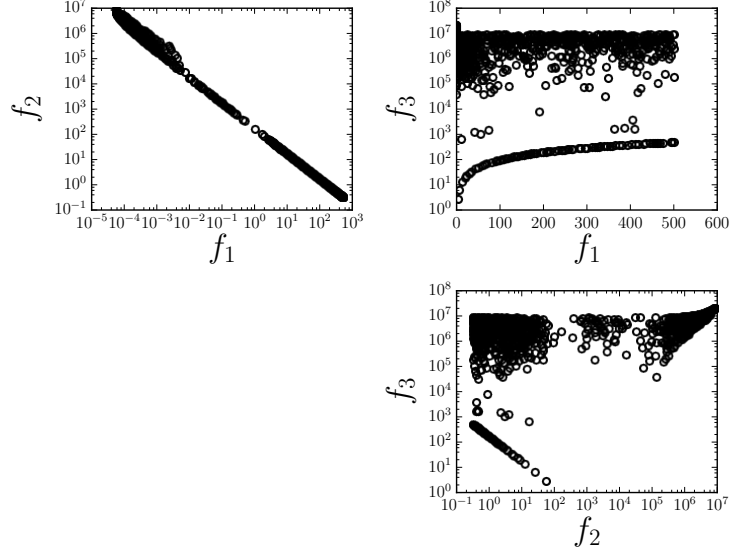


Figure S.1: Scatter matrix of approximated Pareto fronts of the RE3-3-1 problem.

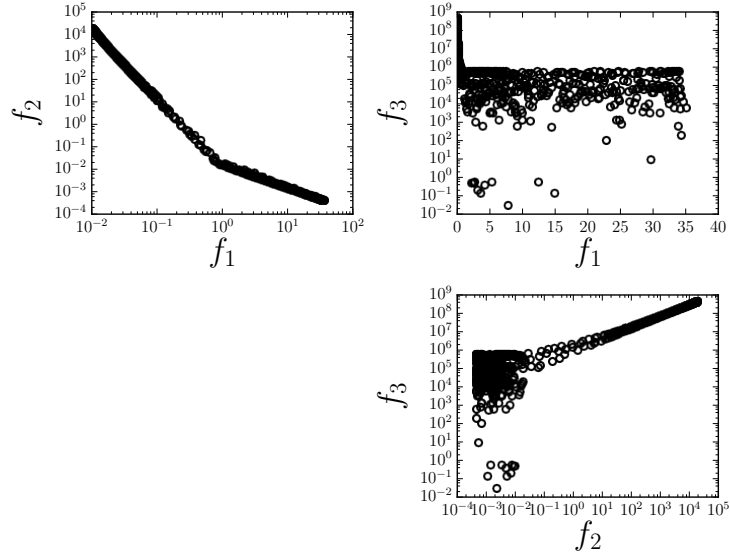


Figure S.2: Scatter matrix of approximated Pareto fronts of the RE3-4-2 problem.

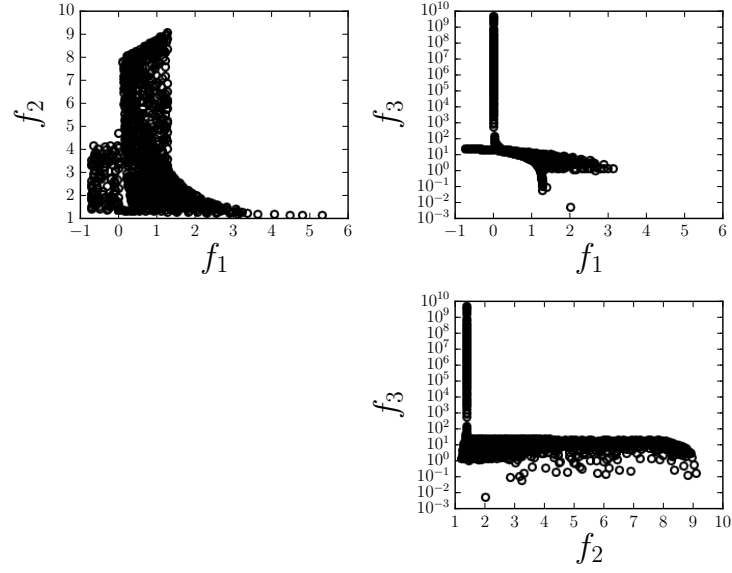


Figure S.3: Scatter matrix of approximated Pareto fronts of the RE3-4-3 problem.

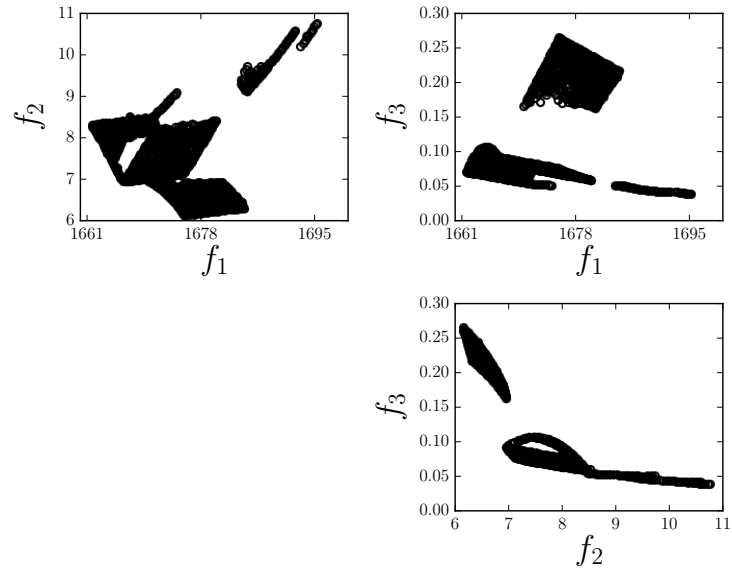


Figure S.4: Scatter matrix of approximated Pareto fronts of the RE3-5-4 problem.

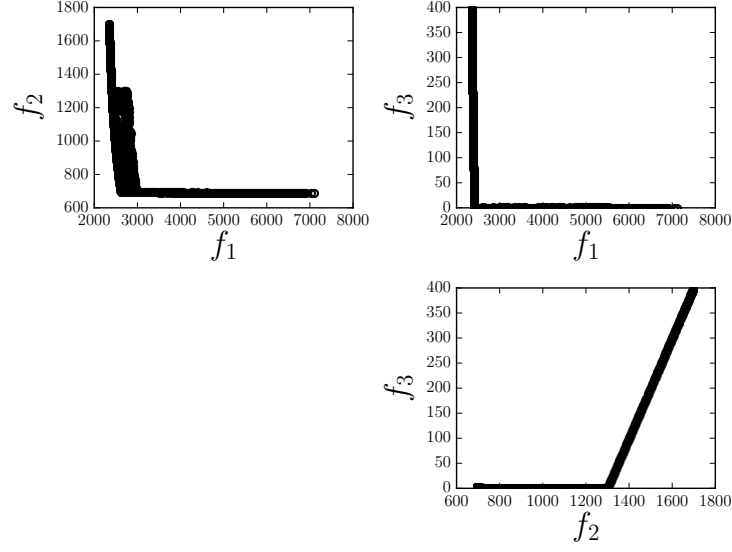


Figure S.5: Scatter matrix of approximated Pareto fronts of the RE3-7-5 problem.

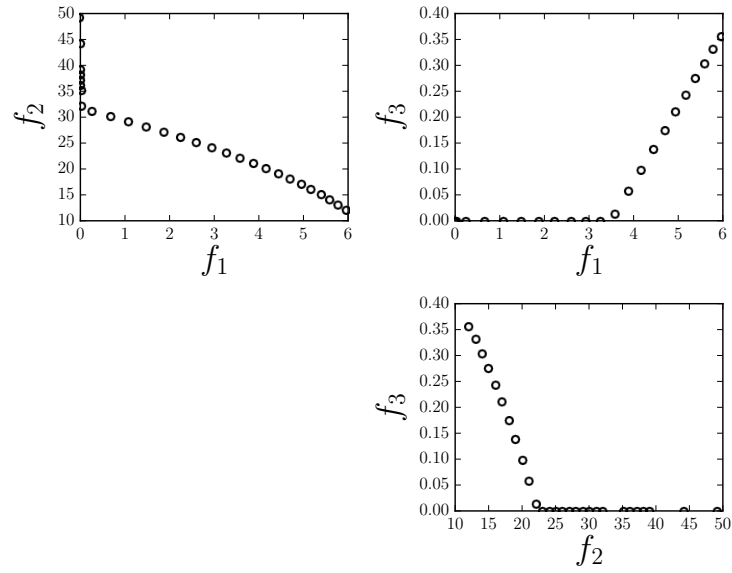


Figure S.6: Scatter matrix of approximated Pareto fronts of the RE3-4-6 problem.

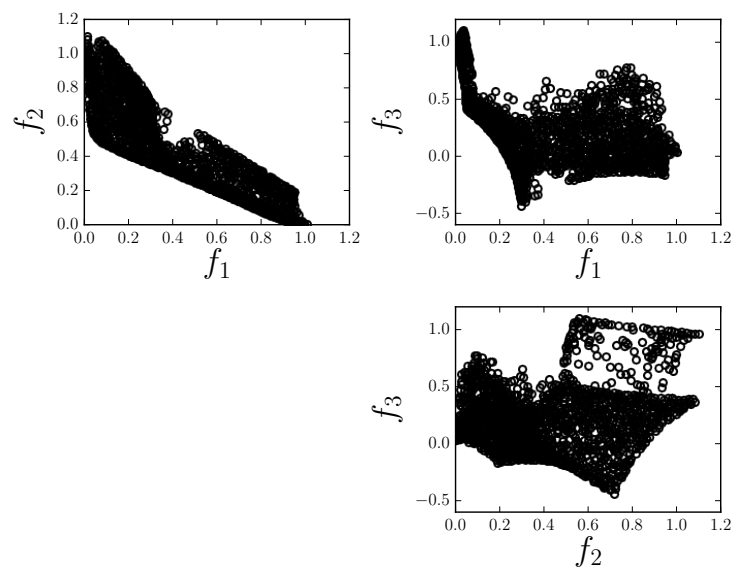


Figure S.7: Scatter matrix of approximated Pareto fronts of the RE3-4-7 problem.

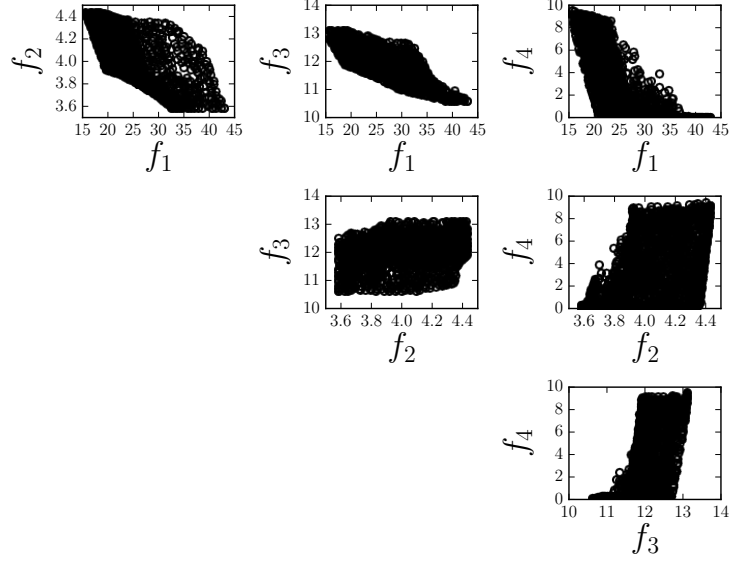


Figure S.8: Scatter matrix of approximated Pareto fronts of the RE4-7-1 problem.

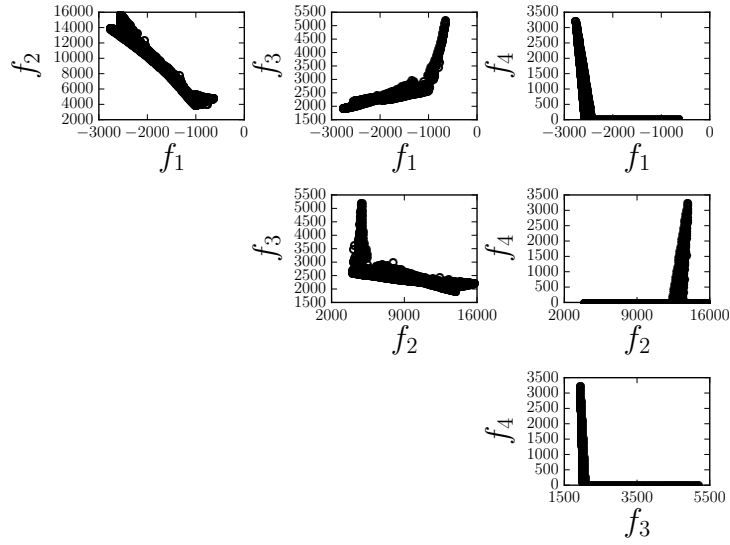


Figure S.9: Scatter matrix of approximated Pareto fronts of the RE4-6-2 problem.

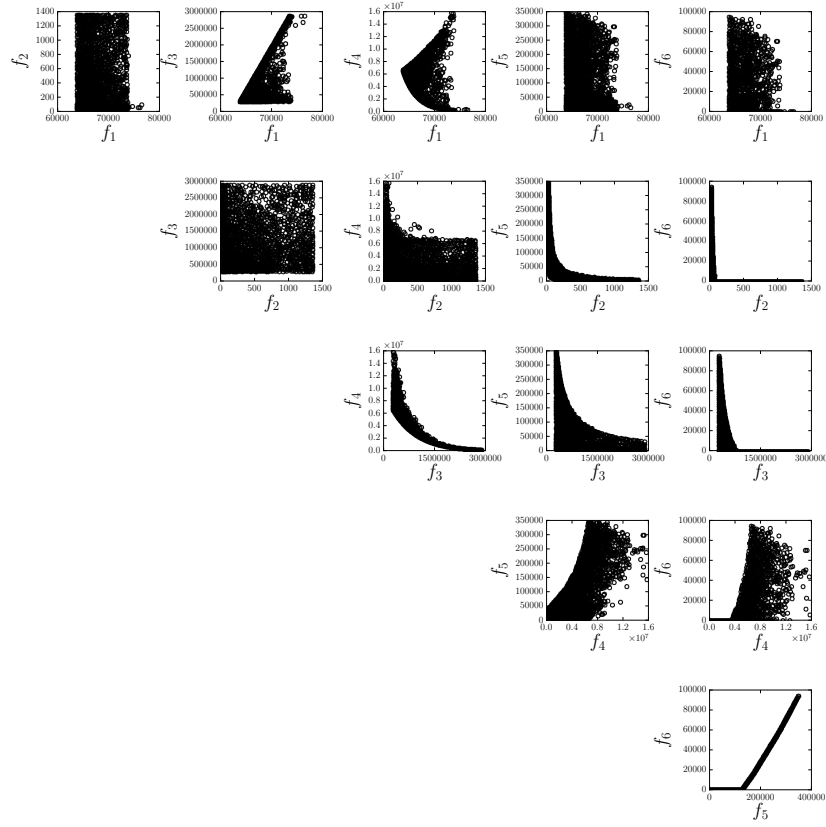


Figure S.10: Scatter matrix of approximated Pareto fronts of the RE6-3-1 problem.

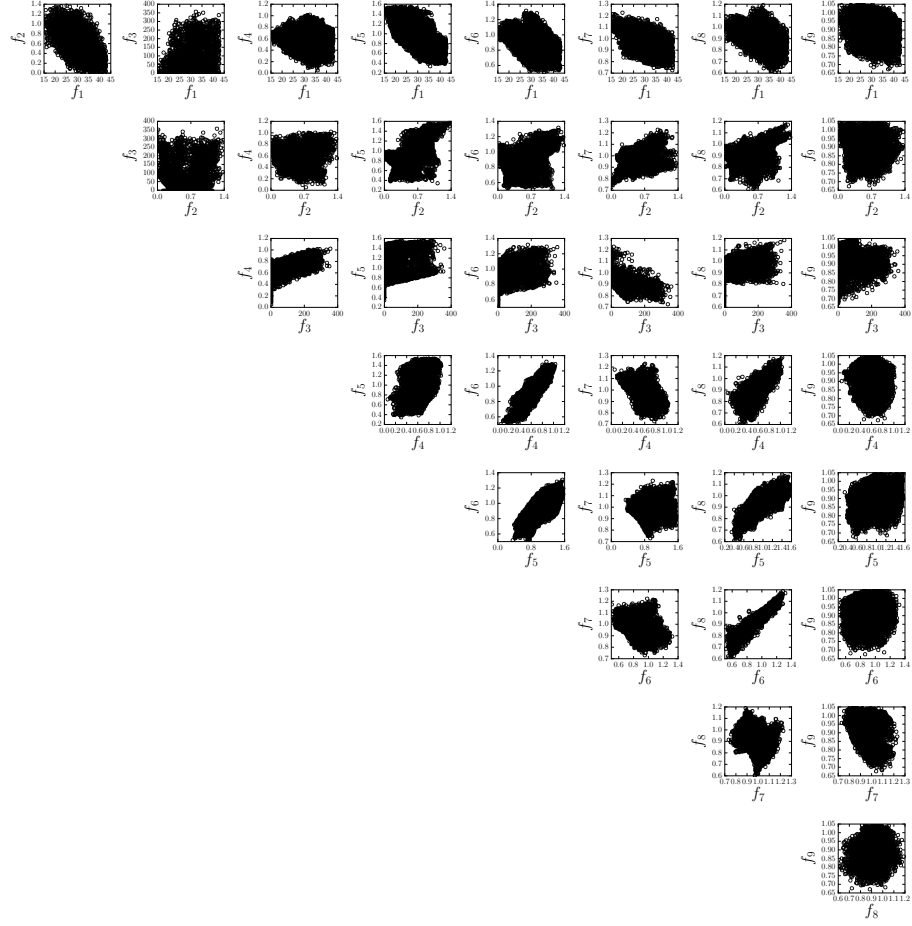


Figure S.11: Scatter matrix of approximated Pareto fronts of the RE9-7-1 problem.



---

**Algorithm S.1:** The distance-based selection method

---

**input** : A set of  $\mu$  non-dominated solutions  $\mathbf{A}$   
**output**: A set of  $n = 500 \times M$  non-dominated solutions  $\mathbf{A}^{\text{approx}}$

```
1  $\mathbf{A}^{\text{approx}} \leftarrow \emptyset$ ;  
2 for  $k \in \{1, \dots, \mu\}$  do  
3    $V_k \leftarrow \text{false}$ ,  $D_k \leftarrow \infty$ ;  
4 for  $i \in \{1, \dots, M\}$  do  
5    $j \leftarrow \underset{k \in \{1, \dots, \mu\} | V_k = \text{false}}{\text{argmin}} f_i(\mathbf{x}_k)$ ;  
6    $\mathbf{A}^{\text{approx}} \leftarrow \mathbf{A}^{\text{approx}} \cup \{\mathbf{x}_j\}$ ,  $V_j \leftarrow \text{true}$ ;  
7   for  $k \in \{1, \dots, \mu\}$  do  
8     if  $V_k = \text{false}$  then  
9        $D_k \leftarrow \min(\text{distance}(\mathbf{x}_k, \mathbf{x}_j), D_k)$ ;  
10 while  $|\mathbf{A}^{\text{approx}}| < n$  do  
11    $j \leftarrow \underset{k \in \{1, \dots, \mu\} | V_k = \text{false}}{\text{argmax}} D_k$ ;  
12    $\mathbf{A}^{\text{approx}} \leftarrow \mathbf{A}^{\text{approx}} \cup \{\mathbf{x}_j\}$ ,  $V_j \leftarrow \text{true}$ ;  
13   for  $k \in \{1, \dots, \mu\}$  do  
14     if  $V_k = \text{false}$  then  
15        $D_k \leftarrow \min(\text{distance}(\mathbf{x}_k, \mathbf{x}_j), D_k)$ ;
```

---

## S.2. The distance-based selection method

We used the distance-based selection method [S.21] to select well-distributed solutions in the objective space from a large number of non-dominated solutions  $\mathbf{A}$  found by various optimizers (see Subsection 3.1). It should be noted that the selection method uses the Euclidean distance in the objective space, not the solution space.

Algorithm S.1 shows the selection method presented in [S.21]. The function  $\text{distance}(\mathbf{x}_1, \mathbf{x}_2)$  in Algorithm S.1 returns the Euclidean distance between two objective vectors  $\mathbf{f}(\mathbf{x}_1)$  and  $\mathbf{f}(\mathbf{x}_2)$ . For each  $i \in \{1, \dots, M\}$ , the  $i$ -th extreme solution that has the minimum objective value  $f_i(\mathbf{x})$  is selected (lines 4–6). The selected  $M$  solutions are added to  $\mathbf{A}^{\text{approx}}$ . Then, a solution that has the maximum distance to solutions in  $\mathbf{A}^{\text{approx}}$  in the objective space is selected (lines 10–12). This procedure is repeatedly performed until  $|\mathbf{A}^{\text{approx}}| = n (= 500 \times M)$ .

## References

- [S.1] F. Y. Cheng, X. S. Li, Generalized center method for multiobjective engineering optimization, Eng. Opt. 31 (5) (1999) 641–661.
- [S.2] H. M. Amir, T. Hasegawa, Nonlinear Mixed-Discrete Structural Optimization, J. Struct. Eng. 115 (3) (1989) 626–646.

- [S.3] B. K. Kannan, S. N. Kramer, An Augmented Lagrange Multiplier Based Method for Mixed Integer Discrete Continuous Optimization and Its Applications to Mechanical Design, *J. Mech. Design* 116 (2) (1994) 405–411.
- [S.4] J. Lampinen, I. Zelinka, Mixed integer-discrete-continuous optimization by differential evolution, part 2: a practical example, in: *Int. Conf. on Soft Comput.*, 1999, pp. 77–81.
- [S.5] C. A. C. Coello, G. T. Pulido, Multiobjective structural optimization using a microgenetic algorithm, *Struct. Multidisc. Optim.* 30 (5) (2005) 388–403.
- [S.6] T. Ray, K. M. Liew, A Swarm Metaphor for Multiobjective Design Optimization, *Eng. Opt.* 34 (2) (2002) 141–153.
- [S.7] X. Liao, Q. Li, X. Yang, W. Zhang, W. Li, Multiobjective optimization for crash safety design of vehicles using stepwise regression model, *Struct. Multidisc. Optim.* 35 (6) (2008) 561–569.
- [S.8] A. Farhang-Mehr, S. Azarm, Entropy-based multi-objective genetic algorithm for design optimization, *Struct. Multidisc. Optim.* 24 (5) (2002) 351–361.
- [S.9] K. Deb, A. Srinivasan, Innovization: Innovative Design Principles Through Optimization, Tech. Rep. KanGAL-2005007, Indian Institute of Technology (2005).
- [S.10] R. Vaidyanathan, K. Tucker, N. Papila, W. Shyy, CFD-Based Design Optimization For Single Element Rocket Injector, in: *AIAA Aerospace Sciences Meeting*, 2003, pp. 1–21.
- [S.11] T. Goel, R. Vaidyanathan, R. T. Haftka, W. Shyy, N. V. Queipo, K. Tucker, Response surface approximation of Pareto optimal front in multi-objective optimization, *Comput. Methods Appl. Mech. Engrg.* 196 (4) (2007) 879–893.
- [S.12] S. Z. Martínez, A. L. Jaimes, A. García-Nájera, LIBEA: A Lebesgue Indicator-Based Evolutionary Algorithm for multi-objective optimization, *SWEVO* 44 (2019) 404–419.
- [S.13] L. Gu, R. J. Yang, C. H. Tho, M. Makowskit, O. Faruquet, Y. Li, Optimisation and robustness for crashworthiness of side impact, *Int. J. Vehicle Design* 26 (4) (2001) 348–360.
- [S.14] K. Deb, S. Gupta, D. A. Daum, J. Branke, A. K. Mall, D. Padmanabhan, Reliability-Based Optimization Using Evolutionary Algorithms, *IEEE TEVC* 13 (5) (2009) 1054–1074.

- [S.15] H. Jain, K. Deb, An evolutionary many-objective optimization algorithm using reference-point based nondominated sorting approach, part II: handling constraints and extending to an adaptive approach, *IEEE TEVC* 18 (4) (2014) 602–622.
- [S.16] M. G. Parsons, R. L. Scott, Formulation of Multicriterion Design Optimization Problems for Solution With Scalar Numerical Optimization Methods, *J. Ship Research* 48 (1) (2004) 61–76.
- [S.17] C. G. Hart, N. Vlahopoulos, An integrated multidisciplinary particle swarm optimization approach to conceptual ship design, *Struct. Multidisc. Optim.* 41 (3) (2010) 481–494.
- [S.18] T. Ray, K. Tai, K. C. Seow, Multiobjective design optimization by an evolutionary algorithm, *Eng. Opt.* 33 (4) (2001) 399–424.
- [S.19] K. Deb, H. Jain, An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part I: solving problems with box constraints, *IEEE TEVC* 18 (4) (2014) 577–601.
- [S.20] Y. Xiang, Y. Zhou, M. Li, Z. Chen, A Vector Angle-Based Evolutionary Algorithm for Unconstrained Many-Objective Optimization, *IEEE TEVC* 21 (1) (2017) 131–152.
- [S.21] R. Tanabe, H. Ishibuchi, A. Oyama, Benchmarking Multi- and Many-objective Evolutionary Algorithms under Two Optimization Scenarios, *IEEE Access* 5 (2017) 19597–19619.