

A Multi-Objective Evolutionary Algorithm Model for Product Form Design Based on Improved SPEA2

Zeng Wang ^{1,2}, Weidong Liu ^{1,*}, Minglang Yang ² and Dongji Han ²

¹ School of Mechatronics Engineering, Nanchang University, Nanchang 330031, China

² School of Art and Design, Nanchang University, Nanchang 330031, China

* Correspondence: liuwd@ncu.edu.cn

Table S1. Nomenclature list.

No.	Abbreviation	Full name	No.	Abbreviation	Full name
1	BPNN	back propagation neural network	20	MDS	multidimensional scaling analysis
2	DA	design analysis	21	MIPM	multi-objective prediction model
3	EFA	elliptic Fourier analysis	22	MO	modification operator
4	EFD	elliptic Fourier descriptor	23	MOEA	multi-objective evolutionary algorithm
5	Entropy-TOPSIS	entropy weight and technique for order preference by similarity to ideal solution	24	MOO	multi-objective optimization
6	FAHP	fuzzy analytic hierarchy process	25	MOPM	multi-objective prediction model
7	FIOCS	final image objective comprehensive score	26	NEFD	normalized elliptic Fourier descriptor
8	FNN	fuzzy neural network	27	NSGA-II	non-dominated sorting genetic algorithm II
9	FTICS	final target image comprehensive score	28	OSS	optimal solution selection
10	GA	genetic algorithm	29	PC	principal component
11	GABP	GA and BPNN	30	PCA	principal component analysis
12	IAMO	improved adaptive mutation operator	31	PFDMOEAM	product form design multi-objective evolutionary algorithm model
13	ICO	improved crossover operator	32	PFIA	product form and image analysis
14	IEMSs	image evaluation mean scores	33	PFR	product form representation
15	IOCSM	image objective comprehensive scoring model	34	RMSE	root mean square error
16	ISPEA2	improved SPEA2	35	SPEA2	strength Pareto evolutionary algorithm

17	KIR	key image recognition	36	SVR	support vector regression
18	KJ	Kawakida Jirou	37	TICSM	target image comprehensive score model
19	MADM	multi-attribute decision-making			

Table S2. PC scores for representative samples.

Sample No.	PC scores						
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7
1	-0.6524	-0.4649	-0.0129	0.1124	-0.1042	-0.0128	-0.0966
2	-0.8519	0.0141	0.0557	0.0293	-0.0554	-0.0103	-0.0219
3	-0.8674	0.1096	-0.1195	0.0349	0.0632	0.0827	-0.0021
4	-0.9821	0.2986	0.1790	0.0242	-0.0226	-0.0022	-0.0524
5	-0.8134	-0.0554	0.0134	-0.0377	0.0335	-0.0271	-0.0001
6	-0.9093	0.1285	-0.1693	0.0617	-0.0801	-0.0239	-0.0172
7	-0.7555	-0.1800	-0.1415	-0.0187	-0.0251	-0.0084	0.0172
8	-0.8346	-0.0293	-0.0396	-0.0197	0.0267	-0.0545	-0.0041
9	-0.5196	-0.6880	0.1064	-0.1021	-0.0661	0.0099	-0.0122
10	-0.8179	-0.0019	-0.0084	0.0712	-0.0026	-0.0746	-0.0626
11	6.3977	-0.4980	-0.0685	-0.0892	0.0438	-0.0609	0.0167
12	-1.1567	0.6116	0.2186	-0.0396	0.0032	0.0446	-0.0195
13	-0.8534	0.0954	-0.1042	0.0000	0.0038	-0.0577	0.0080
14	-1.0002	0.2881	-0.1507	-0.0047	-0.0304	0.0593	0.0244
15	-0.9343	0.2757	-0.1090	0.0876	0.0047	-0.0634	-0.0189
16	-0.9642	0.1747	0.0248	0.0388	0.0226	0.0002	-0.0175
17	-0.8172	-0.0872	-0.0252	-0.0203	0.0113	-0.0186	-0.0026
18	-0.9447	0.1546	-0.0425	-0.0187	-0.0183	0.0581	0.0111
19	-0.4499	-0.6979	0.1645	0.2002	-0.0884	-0.0212	0.0137
20	-0.8111	-0.0202	-0.0488	-0.0529	0.0045	-0.0247	0.0314
21	-1.1525	0.6227	0.0411	0.0141	-0.0934	0.0138	0.0004
22	-0.6715	-0.4253	-0.1529	0.0326	0.1761	0.0993	-0.0759
23	-0.6568	-0.4606	0.1160	-0.0690	-0.0238	0.0500	-0.0211
24	-0.7303	-0.2972	0.0478	-0.0680	-0.0367	-0.0112	0.0090
25	-0.7947	-0.0915	-0.0666	-0.0366	0.0476	-0.0360	0.0192
26	-0.9554	0.3586	0.0280	-0.0730	-0.0568	-0.0022	0.0513
27	-0.9393	0.0225	-0.0624	0.0327	0.0964	0.0084	-0.0169
28	-1.0779	0.4603	-0.0971	0.0200	-0.0697	-0.0079	0.0169
29	-0.9360	0.1984	0.1504	-0.1017	0.0113	0.0333	0.0154
30	-0.7396	-0.1832	-0.0006	-0.0025	0.0842	-0.0339	-0.0139
31	6.5218	-0.3184	0.0499	-0.0748	0.0247	-0.0307	0.0199
32	-0.8625	0.1285	0.0325	-0.0218	0.1110	0.0197	0.0009
33	6.7935	0.2410	-0.0870	0.0311	-0.0238	-0.0050	-0.0184
34	-0.9687	0.3153	0.1830	-0.0448	0.0740	-0.0720	-0.0231
35	-0.5756	-0.3798	0.2126	0.2537	0.0865	0.0208	0.1276
36	-0.7212	-0.3232	-0.1140	-0.0217	-0.0463	0.1028	0.0121
37	-0.5858	-0.4797	-0.1472	-0.0181	0.0001	0.0069	0.0203
38	-1.0434	0.5002	0.0986	0.0242	0.0565	0.0025	-0.0079
39	6.9690	0.5147	-0.0184	0.0891	-0.0486	0.0562	-0.0053
40	-0.7081	-0.3391	0.1752	-0.1176	-0.0312	0.0025	-0.0099

41	−0.8827	0.1796	−0.1716	0.0273	0.0118	−0.0601	0.0412
42	6.8138	0.2840	0.1185	0.0219	0.0103	0.0327	−0.0126
43	−0.7988	−0.1222	0.0611	−0.0322	0.0157	0.0015	0.0001
44	−0.7513	−0.2207	−0.0775	−0.0538	−0.1235	0.0368	0.0363
45	−1.0078	0.3870	−0.0419	−0.0675	0.0234	−0.0227	0.0396

Table S3. Image evaluation mean scores (IEMSs) matrix.

Sample No.	Avant-garde	Dynamic	Elegant	Formal	Generous	Luxurious	Male	Modern	Simple	Smooth	Steady	Unique
1	0.6686	0.8574	0.4882	0.0784	0.3729	0.7345	0.7345	0.9055	0.7849	0.6708	0.7843	0.7078
2	0.5078	0.5561	0.4716	0.2980	0.4863	0.5667	0.7467	0.7604	0.5745	0.4205	1.0667	0.6667
3	0.6853	0.8029	0.5142	−0.2549	0.2969	0.6232	0.4332	0.9961	0.6265	0.7753	0.5196	0.5804
4	0.1529	0.4529	0.6172	0.6078	0.2685	0.3256	0.3256	0.2412	0.3171	0.2878	0.4216	0.6059
5	0.5647	0.6658	0.7211	0.3569	0.3342	0.6147	0.6470	0.7786	0.4675	0.1593	0.5758	0.4353
6	0.3245	0.6446	0.3647	0.4196	0.1787	0.3845	0.5945	0.5912	0.4628	−0.1187	0.4480	0.5667
7	0.5980	0.5931	0.4854	−0.3333	0.4616	0.5535	0.4635	0.7853	0.3768	0.7157	0.6745	0.3529
8	0.5281	−0.2990	0.2583	0.0980	0.5232	0.4675	0.8675	0.7275	0.2566	−0.3353	0.6275	0.5294
9	0.7647	0.6598	0.5931	−0.1373	0.6452	0.6951	0.7951	0.9436	0.3816	0.5101	0.6471	0.8235
10	0.6075	1.0735	0.4382	−0.6275	0.4572	0.4636	0.3436	0.7961	0.6312	0.9034	0.3235	0.6471
11	0.4529	0.4974	0.6304	−0.2333	0.5315	0.7322	0.5622	0.6070	0.6550	0.7416	0.6480	0.1373
12	−0.1373	−0.1225	−0.2735	0.8431	0.4145	0.4956	0.7956	−0.4706	−0.7704	−0.6621	−0.0490	1.5098
13	0.4718	0.3010	0.2853	0.1333	0.4312	0.6273	0.4373	0.7273	0.4434	0.3431	0.4768	0.2373
14	1.0490	0.5324	−0.1500	0.1569	0.5766	0.3913	0.2913	0.7364	0.8059	0.2853	0.5098	0.2745
15	0.3510	0.2353	0.1523	0.2157	0.2334	0.5156	0.3200	0.4363	0.1822	0.1817	0.1863	0.4118
16	0.1353	0.0098	−0.0196	−0.1961	0.2456	0.3612	0.5123	0.3343	0.2875	0.2560	0.3824	−0.2549
17	0.7863	0.9070	0.8032	−0.6667	0.5320	0.6332	0.6432	0.7657	0.4826	0.7326	0.3441	0.9412
18	0.9137	1.0039	0.5613	−0.6490	−0.0156	0.4633	0.5133	0.7103	0.4351	0.7565	0.3157	0.5059
19	0.3431	0.4980	0.7647	0.2745	0.2178	0.6135	0.4435	0.5461	0.4570	0.2269	0.4902	−0.1961
20	0.1510	0.7814	0.4240	−0.0784	0.3200	0.5363	0.3863	0.7005	0.6589	0.7375	0.5490	0.2353
21	0.9367	0.3069	0.2520	0.6667	0.2541	0.4556	0.1156	0.7588	0.6996	0.8645	0.2157	0.6471
22	1.1653	0.9730	0.5402	−0.8039	0.6956	0.7468	0.7368	0.9510	0.7155	1.1708	0.5598	0.8235
23	0.8333	−0.1098	−0.0225	−0.0196	0.1240	0.7655	0.6455	0.4829	0.4014	−0.0277	0.7363	−0.3922
24	0.7875	1.0061	0.5608	−0.4118	0.0345	0.6645	0.3945	0.8407	0.5715	0.9691	0.6167	−0.0980
25	0.7569	0.9480	0.4500	−0.0196	0.6567	0.6447	0.6470	0.8265	0.2826	0.4015	0.6471	0.3333
26	0.2373	0.1667	0.0294	−0.6471	−0.1573	0.3866	0.0966	0.3343	0.4484	0.7183	0.1275	0.1373

27	0.3608	0.2897	0.0784	−0.6471	0.4746	0.4233	0.5330	0.5294	0.4625	0.6954	0.4020	−0.0980
28	0.0216	0.1537	0.2786	0.5392	0.3545	0.2343	0.5943	0.0882	0.0481	−0.0700	0.2363	−0.1176
29	0.3118	−0.1765	0.3363	0.5490	0.6768	0.4324	0.5240	0.5598	0.3624	−0.0992	0.4541	−0.3137
30	0.4929	0.5245	0.5353	0.0980	0.3604	0.5853	0.4553	0.6051	0.4593	0.2044	0.7059	−0.0392
31	0.5980	−0.0343	−0.0980	−0.0333	0.6136	0.7686	0.7286	0.8169	0.5835	0.3711	0.7275	−0.3118
32	0.3098	0.8255	0.5392	−0.3922	0.7580	0.5536	0.5936	0.8261	0.3720	1.1796	0.5794	0.6275
33	0.5987	0.4245	0.7814	−0.4706	0.2775	0.7746	0.4946	1.0030	0.6325	1.0300	0.5343	−0.6863
34	0.0471	−0.0686	−0.0265	−0.1765	0.3468	0.2826	0.4260	0.2755	0.2662	−0.1423	0.3627	0.0588
35	0.7051	0.6846	0.5990	0.2745	0.5294	0.6724	0.6240	0.9304	0.5047	0.7082	0.5804	0.6863
36	0.6314	0.9877	0.3324	−0.3529	0.5878	0.6152	0.8520	0.9079	0.3135	0.7687	0.3833	0.9412
37	0.5176	0.5449	0.5451	−0.0980	0.3324	0.5546	0.5460	0.6549	0.3083	0.2608	0.4902	−0.0980
38	0.1016	0.5735	0.8578	−0.0961	0.2689	0.3131	0.1531	0.1980	0.2659	0.2240	0.3029	−0.3549
39	0.8224	0.5936	0.8706	0.0392	0.5920	0.7732	0.4632	0.8786	0.5055	0.8126	0.4167	0.2176
40	0.6078	0.6147	0.5775	0.1176	0.2580	0.6669	0.4969	0.7418	0.4792	0.6480	0.7078	0.3725
41	0.3157	0.0931	0.2176	−0.4118	0.2124	0.5354	0.1154	0.6549	0.4029	0.8243	0.3431	−0.2941
42	0.8118	0.6324	0.6382	−0.4706	0.6580	0.7635	0.6350	1.0010	0.7476	1.1691	0.6441	0.4118
43	0.5852	0.2701	0.1657	0.2961	0.4243	0.5300	0.5400	0.7025	0.4875	0.5518	0.4892	−0.2549
44	0.6137	0.7123	0.4686	−0.2308	0.5456	0.5376	0.4376	0.6951	0.5138	0.5726	0.7943	0.6235
45	0.9510	0.5845	0.2269	−0.2490	−0.0746	0.4263	0.1963	0.6936	0.3857	0.5415	0.3676	0.5059

Table S4. PC scores and target adjective calculation scores of 30 Pareto solutions.

Pareto solution No.	PC scores							Target adjective calculation scores		
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	Luxurious	Steady	Modern
1	0.9564	−0.2037	0.7010	0.1723	−0.5363	−0.3322	0.2388	1.6795	2.5615	2.0556
2	0.9310	−0.6500	0.3579	−0.1656	−0.0699	−0.3678	0.2673	1.6617	2.4621	2.1770
3	0.9726	−0.2885	0.7023	−0.0428	−0.9430	−0.4845	0.6788	1.8728	1.9883	2.0278
4	0.9908	−0.1299	0.6543	−0.0699	−0.9162	−0.2597	−0.7542	2.0100	1.9196	1.8113
5	0.9453	−0.2549	0.4263	−0.2205	−0.3859	−0.3979	−0.2753	2.2830	0.6695	1.8448
6	0.8825	0.3751	0.2984	−0.1685	−0.2454	−0.1970	−0.2192	1.7549	0.9408	2.3410
7	0.9949	−0.5920	0.4877	0.0764	−0.5240	−0.1886	0.1235	1.6796	3.1099	2.0175
8	0.9953	0.1549	0.9263	−0.4205	−0.6859	−0.1979	−0.6753	1.9792	2.5281	1.6693
9	0.9825	−0.1751	0.2984	−0.1685	−0.4301	−0.3580	−0.6725	1.7722	1.5778	2.2506
10	0.9596	−0.1858	0.8616	0.1752	−0.0153	−0.4189	0.8688	1.5468	1.9953	2.3201
11	0.8930	−0.2102	0.9670	0.1881	−0.5244	−0.5088	0.5641	1.3096	2.3994	2.4247
12	0.9868	0.2437	0.6959	−0.3677	0.0797	−0.1487	−0.2960	2.3894	1.0365	1.4392
13	0.8826	0.4123	0.3786	−0.1900	−0.6958	−0.2413	−0.1054	2.3134	1.1682	1.5316

14	0.8905	-0.5725	0.9730	-0.1903	-0.4989	-0.3266	0.2378	1.1986	1.7443	2.5668
15	0.9010	0.3155	0.5609	-0.5144	-0.1256	-0.1594	0.1006	2.3363	0.4307	1.6957
16	0.9969	-0.1515	0.3906	-0.5615	-0.4399	-0.3601	-0.4546	1.4571	2.5318	2.3431
17	0.8956	-0.0676	0.2341	-0.2338	-0.2140	-0.3084	0.2815	1.2124	1.5272	2.6007
18	0.9684	0.0600	-0.4004	-0.3611	0.1137	0.1526	-0.4615	2.1791	1.1688	1.7183
19	0.9821	0.1819	0.6481	-0.1204	-0.7263	-0.3718	0.6749	2.2972	1.0802	1.6573
20	0.9019	0.0008	0.6078	-0.3355	-0.7157	-0.2982	0.2732	2.4154	0.8130	1.3693
21	0.9944	-0.5047	0.5768	-0.1500	-0.4158	-0.2796	0.2640	2.1044	1.9807	1.7845
22	0.9938	-0.2627	0.1436	-0.5898	-0.5082	-0.4075	0.3981	1.5401	2.5628	2.1865
23	0.9349	-0.0028	0.5044	0.0430	-0.7407	-0.3180	0.3870	2.0021	1.2411	1.9904
24	0.9993	-0.4985	0.5539	-0.2791	-0.7873	-0.3084	0.3626	1.9418	2.1884	1.8571
25	0.9941	-0.1659	0.3469	-0.1714	-0.4145	-0.4289	-0.2622	2.3310	1.8165	1.2642
26	0.9988	-0.1619	0.3512	-0.5983	-0.4142	-0.3302	0.4411	2.2418	1.5539	1.5578
27	0.9941	-0.9612	0.3871	-0.5159	-0.4292	-0.3978	0.6753	1.9118	1.8069	1.9824
28	0.9997	-0.6696	-0.3893	-0.0661	-0.5233	-0.4306	-0.2068	1.4692	2.8111	2.2728
29	0.9992	-0.1902	0.1403	0.1720	-0.7739	-0.2751	0.8750	1.9171	2.3182	1.7570
30	0.9860	-0.7984	-0.5883	-0.1842	-0.5177	-0.3787	0.1766	1.7074	2.9124	1.9477
