

Mechanical Performance over Energy Expenditure in MEX 3D Printing of Polycarbonate: A Multiparametric Optimization with the Aid of Robust Experimental Design

Nectarios Vidakis ^{1,*}, Markos Petousis ¹, Constantine N. David ², Dimitrios Sagris ², Nikolaos Mountakis ¹ and Emmanuel Karapidakis ³

¹ Department of Mechanical Engineering, Hellenic Mediterranean University, 71410 Heraklion, Greece

² Department of Mechanical Engineering, International Hellenic University, 62124 Serres, Greece

³ Electrical and Computer Engineering Dept., Hellenic Mediterranean University, 71410 Heraklion, Greece

* Correspondence: vidakis@hmu.gr; Tel.: +30-2810379227

Abstract: A single paragraph of about 200 words maximum. For research articles, abstracts should give a pertinent overview of the work. We strongly encourage authors to use the following style of structured abstracts, but without headings: (1) Background: Place the question addressed in a broad context and highlight the purpose of the study; (2) Methods: briefly describe the main methods or treatments applied; (3) Results: summarize the article's main findings; (4) Conclusions: indicate the main conclusions or interpretations. The abstract should be an objective representation of the article and it must not contain results that are not presented and substantiated in the main text and should not exaggerate the main conclusions.

Keywords: Sustainable Additive Manufacturing; Polycarbonate (PC); Optimization; Material Extrusion (MEX); Energy consumption; Compression Test; Taguchi Analysis; Robust Design

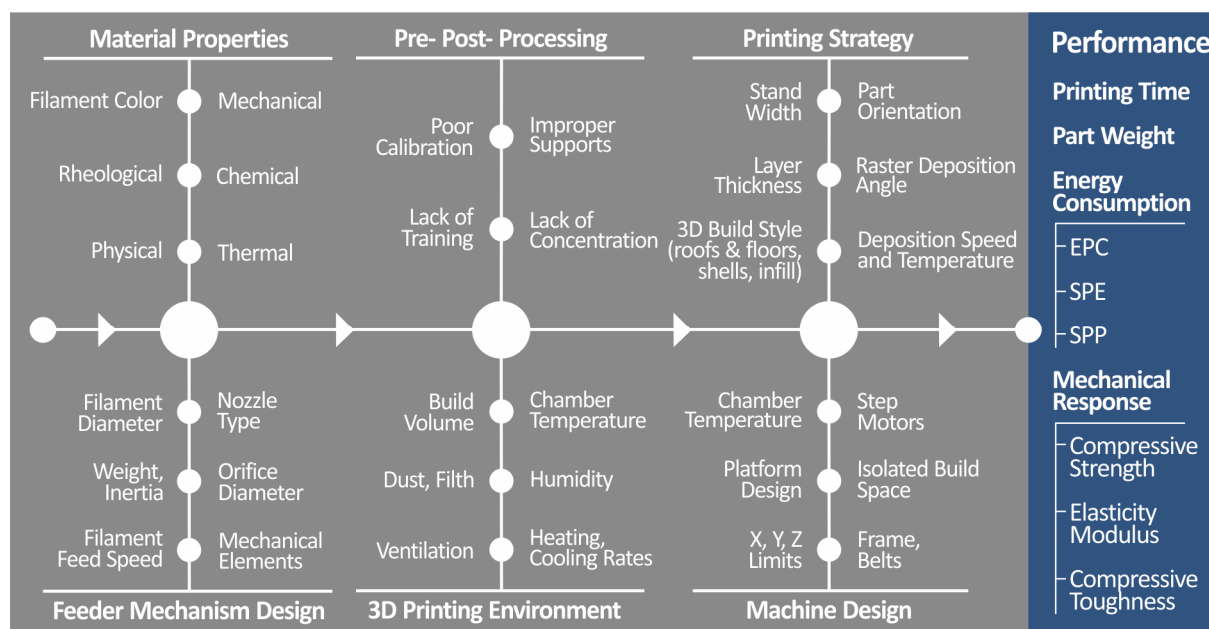


Figure S1. Cause and effect diagram, indicating the parameters affecting the performance of the 3D printed parts regarding the energy consumption and the mechanical response under compression loading.

Morphological examination

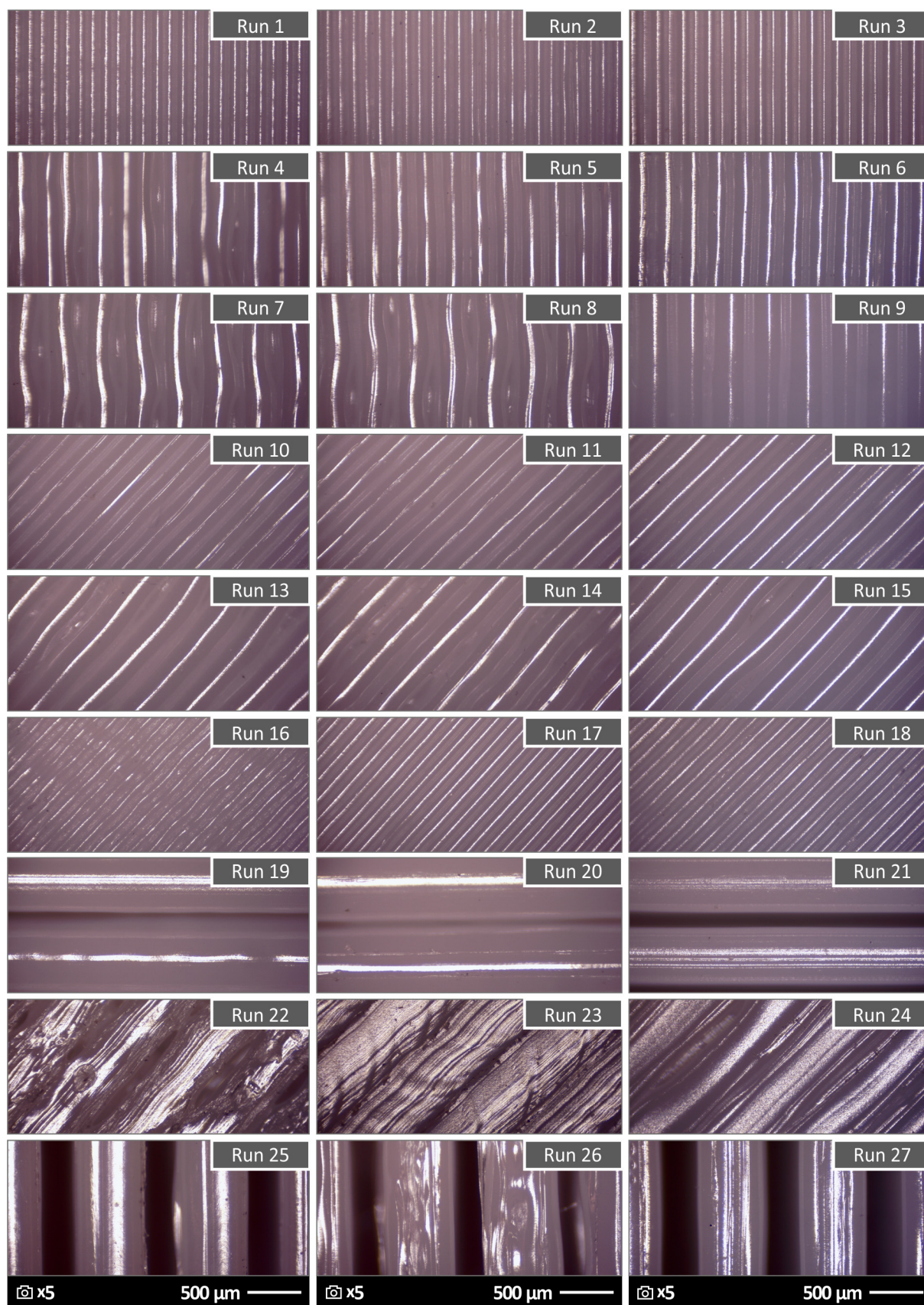


Figure S2. Typical samples 3D printed with the various control parameters' values.

Design of experiment and experimental results

Supplementary Table S1. Measured Weight, Printing Time, Compressive Strength, Compressive Modulus of Elasticity and Compressive Toughness for each experimental run and five replicas per run.

A/A	Run	Weight (g)	Printing Time (sec)	sB [MPa]	E [MPa]	Toughness [MJ/m ³]
1	1	6.49	6041	48.78	1035.20	4.30
2		7.06	9215	49.78	1100.42	4.36
3		6.90	6094	49.36	1112.78	4.42
4		6.81	9048	40.60	949.49	4.10
5		6.90	6196	49.73	1116.76	4.16
6	2	8.69	3536	50.50	1154.38	4.69
7		8.19	3664	50.43	1117.93	4.71
8		8.29	5411	51.33	1128.60	4.73
9		8.19	5371	50.31	1129.13	4.75
10		8.29	3648	51.03	1131.82	4.44
11	3	6.78	2882	50.08	1084.87	4.91
12		6.70	2778	52.15	1157.44	4.76
13		6.70	4201	52.74	1110.64	6.02
14		6.70	2786	51.36	1109.22	5.31
15		6.62	4054	51.83	1128.31	5.11
16	4	8.15	3109	59.39	1190.84	8.02
17		8.23	3043	59.14	1209.84	7.74
18		8.23	3132	58.69	1179.18	7.72
19		8.56	4409	58.78	1194.51	7.63
20		8.48	4416	58.43	1182.33	7.64
21	5	8.94	2296	61.03	1202.96	8.07
22		7.92	2337	61.47	1200.62	8.08
23		8.26	2351	60.37	1218.73	7.88
24		8.43	3404	61.03	1189.16	7.83
25		8.77	2397	59.94	1172.44	7.80
26	6	7.47	2081	64.34	1193.22	8.63
27		7.38	2151	64.03	1188.51	8.44
28		7.55	1447	61.80	1159.58	7.76
29		7.71	1488	61.69	1079.11	7.92
30		8.29	2174	62.34	1157.69	8.01
31	7	9.50	3137	64.55	1188.42	8.99
32		9.50	4688	62.20	1129.87	8.99
33		9.42	3020	64.86	1118.62	9.22
34		9.68	3182	68.14	1179.35	9.78
35		9.50	3129	61.66	1100.38	8.76
36	8	9.50	1700	62.68	1109.91	8.76
37		9.42	1771	61.87	1182.82	8.55
38		9.50	2605	62.38	1245.40	8.65
39		9.42	1843	63.47	1176.91	8.74
40		9.50	1846	63.46	1119.78	8.90
41	9	9.13	1790	62.33	1156.07	8.76

42		9.56	1265	63.33	1176.49	8.69
43		9.47	1199	61.34	1184.38	8.21
44		9.39	1834	60.99	1193.49	8.16
45		9.56	1287	62.72	1177.02	8.40
46		9.77	7865	55.29	956.93	7.63
47		9.68	5652	51.93	739.49	8.27
48	10	9.21	7667	55.80	881.56	8.48
49		9.40	5535	59.46	985.16	8.76
50		9.68	7812	56.73	870.96	8.54
51		9.41	3520	56.57	892.22	8.84
52		9.50	4882	55.69	863.71	8.72
53	11	9.50	5045	55.39	797.67	5.04
54		9.41	3397	52.24	715.20	8.56
55		9.41	4896	55.61	859.24	8.53
56		8.88	4276	57.21	891.69	8.98
57		8.79	2911	57.48	834.67	9.18
58	12	8.79	4072	55.26	873.38	8.86
59		8.88	2864	56.06	913.60	8.82
60		8.71	2987	57.37	926.60	8.91
61		5.77	4819	24.92	369.51	3.79
62		5.84	4641	25.41	393.80	3.87
63	13	5.77	3400	24.51	410.00	3.76
64		5.77	4671	23.86	430.71	3.74
65		5.84	4759	25.04	447.44	3.63
66		6.55	2123	26.57	442.40	4.21
67		6.70	3160	25.56	396.51	4.00
68	14	6.63	2210	26.08	497.44	4.12
69		6.55	2289	26.47	408.18	4.23
70		6.63	2213	26.61	444.89	4.23
71		6.52	1799	24.98	525.53	3.88
72		6.44	1738	20.92	437.91	3.41
73	15	6.69	2594	25.27	472.16	3.88
74		6.60	1729	22.27	452.60	3.35
75		6.60	2616	22.28	490.80	2.36
76		7.67	9511	29.97	561.18	4.10
77		8.71	9453	30.98	410.49	4.44
78	16	7.82	9751	33.14	575.76	4.51
79		8.09	9288	40.65	446.64	6.37
80		8.48	9417	35.41	625.20	4.85
81		8.28	8436	32.30	613.22	4.30
82		8.38	8721	29.11	609.36	4.23
83	17	8.28	5659	28.31	416.13	4.18
84		8.19	5899	28.48	554.42	4.18
85		8.38	5890	28.57	586.98	4.22
86	18	7.98	6862	34.81	643.98	5.18
87		8.16	4786	35.45	691.89	5.38

88		8.42	6651	35.54	729.91	4.87
89		8.33	4514	35.67	732.47	5.40
90		8.16	6826	35.53	670.80	5.00
91		7.46	2321	56.95	1133.58	4.41
92		7.38	2502	58.99	1174.38	3.78
93	19	7.38	3301	50.45	1119.73	3.14
94		7.46	3392	57.42	1124.82	4.03
95		7.38	2212	47.84	1161.42	2.88
96		7.37	1125	46.93	904.69	5.27
97		7.20	1127	40.13	1020.84	2.99
98	20	7.03	1084	38.55	999.47	3.48
99		7.12	1050	44.51	766.13	4.48
100		7.28	1624	23.26	1081.09	1.49
101		6.54	1719	36.63	974.31	2.31
102		6.62	1716	38.36	839.96	3.84
103	21	6.78	1762	36.87	944.71	2.85
104		6.70	2484	23.07	914.49	1.82
105		6.78	1784	37.29	695.07	3.77
106		7.25	9278	61.19	973.51	9.41
107		7.75	9086	68.57	1197.67	9.16
108	22	7.41	6042	65.82	1120.04	9.63
109		7.95	6082	68.67	1221.67	9.61
110		7.33	8807	61.89	1178.62	9.08
111		9.87	10485	68.34	1103.33	8.02
112		9.77	10097	62.83	1129.40	8.72
113	23	8.89	6966	70.81	1159.02	9.45
114		9.96	6939	67.73	1017.80	9.70
115		9.67	6972	65.69	1126.93	9.39
116		8.39	3111	45.40	734.33	5.75
117		8.85	3954	46.41	628.29	6.74
118	24	9.32	3194	59.45	1001.22	7.85
119		8.85	4762	54.61	762.78	7.54
120		8.35	4749	55.27	959.60	7.15
121		6.74	2543	17.56	322.20	2.19
122		6.57	2671	18.73	333.42	2.53
123	25	6.83	1805	14.81	354.69	2.16
124		6.48	2630	16.03	302.53	2.22
125		6.48	1855	15.83	346.87	2.36
126		6.28	2216	16.93	355.47	2.32
127		6.04	2171	21.91	377.18	2.59
128	26	6.20	1510	21.22	379.00	2.48
129		6.12	1430	21.55	373.64	2.68
130		6.12	2132	21.27	398.27	2.60
131		6.61	1158	22.56	468.36	3.05
132	27	6.44	761	24.63	457.56	3.42
133		6.52	1129	21.28	213.20	2.90

134	6.35	809	23.58	508.47	3.24
135	6.44	1123	24.17	528.44	3.40
Min:	5.77	761.00	14.81	213.20	1.49
Max:	9.96	10485.00	70.81	1245.40	9.78
Average:	7.88	3962.46	45.73	860.02	5.88

Supplementary Table S2. Measured for EPC, SPE, SPP, Area to Nominal and Volume to Nominal for each experimental run and five replicas per run.

A/A	Run	EPC (MJ)	SPE (MJ/g)	SPP (kW/g)	Area 2 Nom [%]	Volume 2 Nom [%]
1	1	1.728	0.266	0.044	70.7%	67.8%
2		1.764	0.250	0.027	70.4%	67.3%
3		1.836	0.266	0.044	71.7%	68.6%
4		1.080	0.159	0.018	72.2%	69.0%
5		1.728	0.250	0.040	71.6%	68.1%
6	2	1.152	0.133	0.037	97.6%	97.2%
7		1.908	0.233	0.064	97.3%	96.8%
8		2.052	0.248	0.046	96.3%	95.9%
9		2.016	0.246	0.046	97.0%	96.3%
10		1.980	0.239	0.065	96.8%	96.0%
11	3	0.936	0.138	0.048	101.3%	100.8%
12		1.008	0.150	0.054	101.2%	100.4%
13		0.972	0.145	0.035	101.0%	100.4%
14		1.620	0.242	0.087	100.9%	100.0%
15		1.548	0.234	0.058	101.0%	100.2%
16	4	1.224	0.150	0.048	99.9%	100.1%
17		1.188	0.144	0.047	99.6%	99.6%
18		0.756	0.092	0.029	99.4%	99.4%
19		0.684	0.080	0.018	99.3%	99.2%
20		1.188	0.140	0.032	99.6%	99.1%
21	5	0.792	0.089	0.039	101.8%	100.3%
22		0.828	0.105	0.045	103.0%	101.4%
23		0.828	0.100	0.043	102.1%	100.6%
24		0.828	0.098	0.029	102.1%	100.1%
25		1.368	0.156	0.065	101.8%	99.7%
26	6	0.756	0.101	0.049	99.1%	97.8%
27		0.684	0.093	0.043	99.1%	97.5%
28		1.260	0.167	0.115	99.6%	98.2%
29		0.684	0.089	0.060	99.8%	97.9%
30		0.756	0.091	0.042	99.6%	97.6%
31	7	0.792	0.083	0.027	102.7%	100.3%
32		0.720	0.076	0.016	102.9%	100.4%
33		0.720	0.076	0.025	103.8%	101.8%
34		0.756	0.078	0.025	103.5%	101.5%
35		1.296	0.136	0.044	103.3%	101.0%
36	8	0.684	0.072	0.042	97.7%	96.1%
37		1.080	0.115	0.065	98.3%	96.4%

38		0.648	0.068	0.026	97.8%	96.3%
39		1.116	0.118	0.064	99.5%	98.0%
40		0.648	0.068	0.037	98.6%	96.8%
41		0.720	0.079	0.044	104.0%	103.0%
42		0.720	0.075	0.060	103.9%	103.1%
43	9	0.396	0.042	0.035	104.5%	103.6%
44		0.468	0.050	0.027	103.2%	102.4%
45		0.396	0.041	0.032	105.0%	104.0%
46		2.052	0.210	0.027	98.1%	97.8%
47		2.016	0.208	0.037	97.2%	97.1%
48	10	1.188	0.129	0.017	97.8%	97.7%
49		2.016	0.214	0.039	98.0%	97.6%
50		1.188	0.123	0.016	97.2%	96.5%
51		1.188	0.126	0.036	100.1%	99.3%
52		1.260	0.133	0.027	99.3%	98.6%
53	11	1.224	0.129	0.026	100.1%	99.3%
54		0.720	0.077	0.023	99.0%	98.3%
55		1.188	0.126	0.026	99.8%	99.5%
56		1.764	0.199	0.046	98.1%	97.9%
57		0.972	0.111	0.038	98.0%	97.8%
58	12	1.800	0.205	0.050	98.9%	98.8%
59		1.692	0.191	0.067	98.4%	98.1%
60		1.692	0.194	0.065	98.3%	98.5%
61		1.080	0.187	0.039	97.0%	97.0%
62		1.008	0.173	0.037	96.9%	97.0%
63	13	0.648	0.112	0.033	96.0%	95.7%
64		1.044	0.181	0.039	96.5%	96.6%
65		1.044	0.179	0.038	97.5%	97.1%
66		0.432	0.066	0.031	97.2%	97.1%
67		0.432	0.064	0.020	99.5%	100.1%
68	14	0.432	0.065	0.029	96.8%	97.3%
69		0.720	0.110	0.048	97.1%	97.6%
70		0.720	0.109	0.049	98.9%	99.0%
71		0.864	0.133	0.074	101.6%	101.4%
72		0.540	0.084	0.048	100.8%	100.6%
73	15	0.900	0.135	0.052	98.5%	98.4%
74		0.900	0.136	0.079	100.2%	100.0%
75		0.576	0.087	0.033	101.6%	101.5%
76		4.523	0.590	0.062	98.7%	98.1%
77		3.564	0.409	0.043	101.3%	100.7%
78	16	3.996	0.511	0.052	98.8%	98.5%
79		4.154	0.513	0.055	98.2%	97.6%
80		3.780	0.446	0.047	98.9%	98.1%
81		2.237	0.270	0.032	98.6%	98.8%
82	17	1.296	0.155	0.018	98.9%	98.9%
83		2.088	0.252	0.045	97.2%	97.2%

84		2.439	0.298	0.050	98.0%	98.2%
85		1.152	0.137	0.023	98.4%	98.3%
86		1.296	0.162	0.024	103.1%	102.6%
87		2.016	0.247	0.052	101.3%	100.9%
88	18	1.296	0.154	0.023	100.8%	100.5%
89		2.088	0.251	0.056	101.4%	100.9%
90		1.944	0.238	0.035	101.1%	100.9%
91		1.764	0.236	0.102	99.6%	99.5%
92		1.764	0.239	0.096	99.6%	99.5%
93	19	1.008	0.137	0.041	99.1%	98.8%
94		1.044	0.140	0.041	99.4%	99.3%
95		1.080	0.146	0.066	99.4%	99.1%
96		0.828	0.112	0.100	97.7%	97.3%
97		0.468	0.065	0.058	98.0%	97.5%
98	20	0.468	0.067	0.061	99.2%	98.6%
99		0.792	0.111	0.106	98.9%	98.3%
100		0.504	0.069	0.043	98.7%	98.0%
101		0.828	0.127	0.074	90.8%	90.5%
102		0.504	0.076	0.044	91.1%	90.5%
103	21	0.468	0.069	0.039	90.9%	90.3%
104		0.432	0.064	0.026	91.7%	91.2%
105		0.468	0.069	0.039	91.2%	90.6%
106		5.436	0.750	0.081	97.3%	96.8%
107		5.436	0.701	0.077	98.0%	97.3%
108	22	3.492	0.471	0.078	98.7%	98.0%
109		5.292	0.666	0.109	98.2%	97.9%
110		5.328	0.727	0.083	97.9%	97.4%
111		5.076	0.514	0.049	103.3%	103.4%
112		4.729	0.484	0.048	102.4%	102.4%
113	23	5.580	0.628	0.090	102.5%	102.8%
114		5.040	0.506	0.073	103.8%	103.9%
115		5.256	0.544	0.078	103.4%	103.4%
116		3.204	0.382	0.123	98.1%	98.0%
117		4.883	0.552	0.140	97.7%	97.5%
118	24	3.060	0.328	0.103	97.6%	97.3%
119		2.709	0.306	0.064	98.4%	98.2%
120		2.912	0.349	0.073	96.8%	96.4%
121		0.252	0.037	0.015	97.9%	97.4%
122		0.252	0.038	0.014	97.4%	97.1%
123	25	0.252	0.037	0.020	97.4%	97.0%
124		0.432	0.067	0.025	97.6%	97.1%
125		0.432	0.067	0.036	97.4%	97.0%
126		0.756	0.120	0.054	97.9%	97.6%
127	26	0.684	0.113	0.052	96.3%	95.9%
128		1.224	0.197	0.131	97.7%	97.3%
129		0.720	0.118	0.082	97.6%	97.3%

130		0.756	0.124	0.058	96.6%	96.1%
131		0.216	0.033	0.028	100.8%	100.8%
132		0.360	0.056	0.073	100.8%	100.6%
133	27	0.360	0.055	0.049	101.6%	101.3%
134		0.360	0.057	0.070	100.3%	100.1%
135		0.360	0.056	0.050	100.5%	100.1%
Min:		0.216	0.033	0.014	70.4%	67.3%
Max:		5.580	0.750	0.140	105.0%	104.0%
Average:		1.531	0.190	0.050	98.1%	97.5%

Statistical analysis

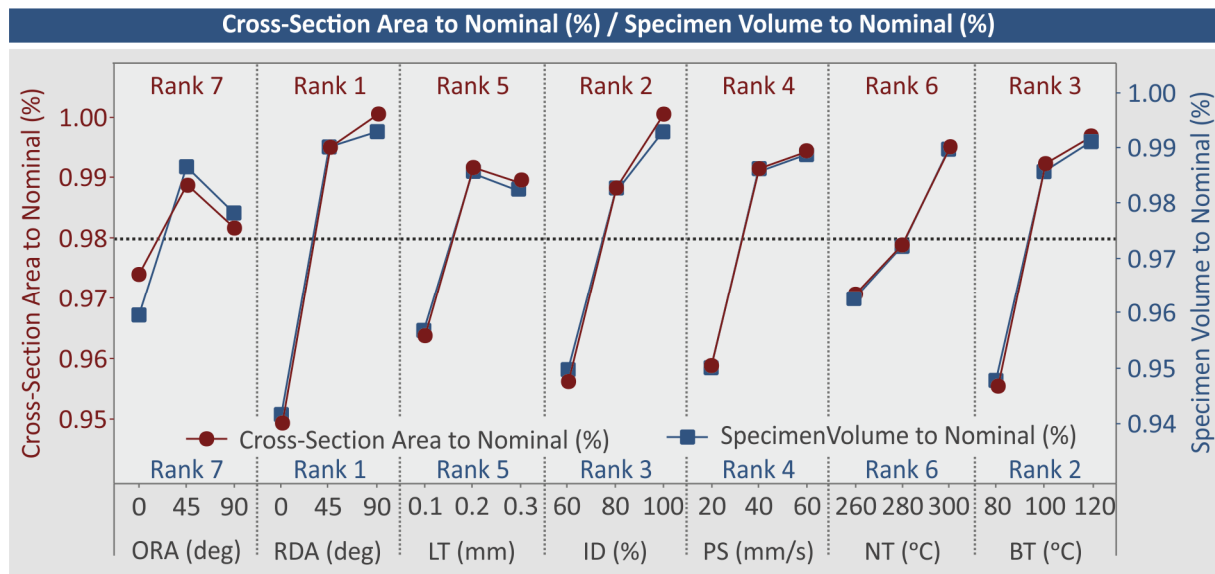


Figure S3. MEP for the area to nominal (%) and the volume to nominal (%) vs the control parameters of the work.

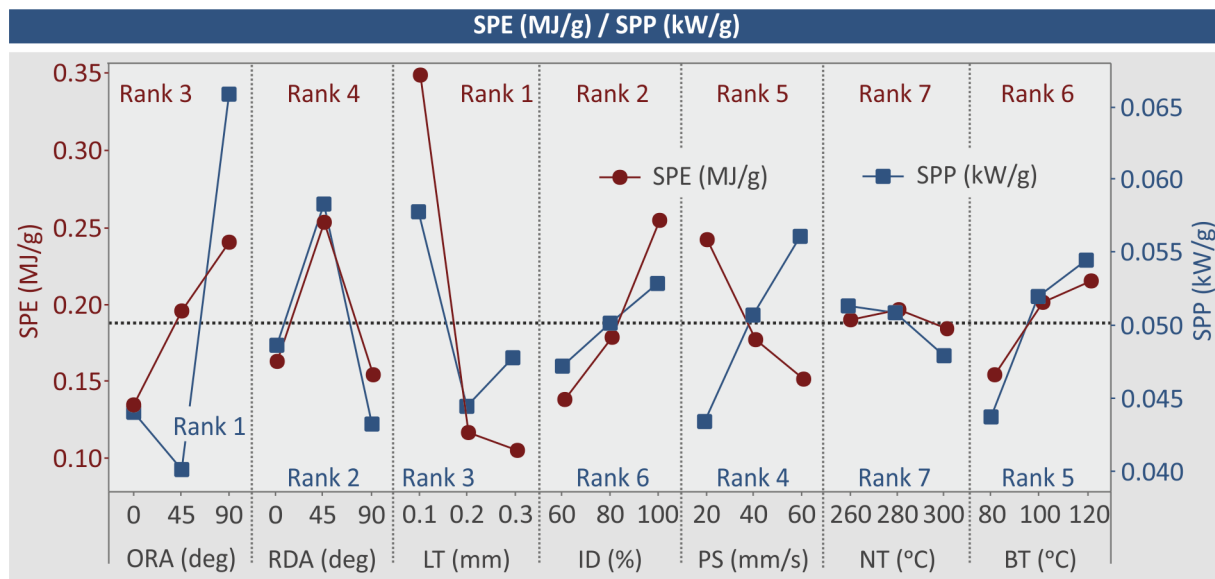


Figure S4. MEP for the SPE (MJ/g) and the SPP (kW/g) vs the control parameters of the work.

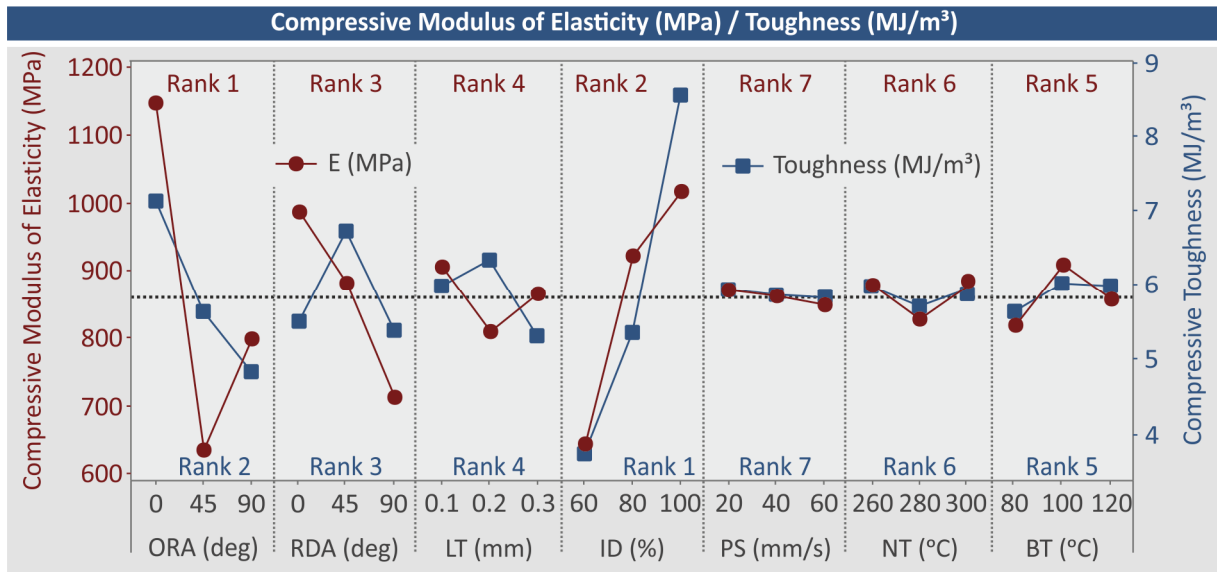


Figure S5. MEP for the compressive modulus of elasticity (MPa) and the compressive toughness (MJ/m³) vs the control parameters of the work.

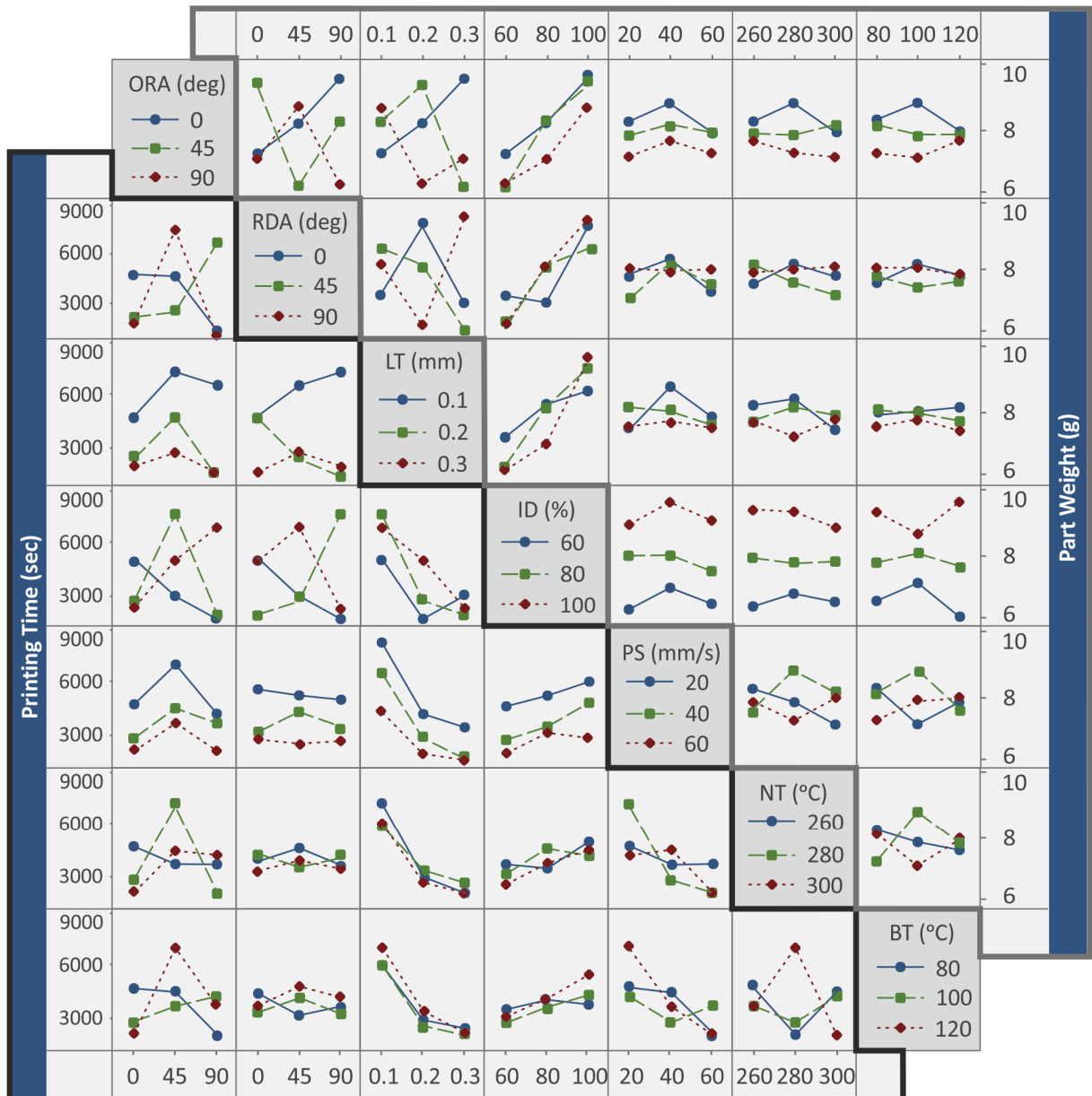


Figure S6. Interaction plots for the printing time (sec) and the part weight (g) vs the control parameters of the work.

Regression analysis

Supplementary Table S3. Polynomial ANOVA, Weight vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	168.979	12.0699	60.09	0.000
ORA	1	0.513	0.5130	2.55	0.113
RDA	1	1.268	1.2675	6.31	0.013
LT	1	0.085	0.0848	0.42	0.517
ID	1	0.182	0.1822	0.91	0.343
PS	1	5.873	5.8734	29.24	0.000
NT	1	0.489	0.4886	2.43	0.121
BT	1	0.219	0.2193	1.09	0.298
ORA ²	1	0.265	0.2651	1.32	0.253
RDA ²	1	1.900	1.9001	9.46	0.003
LT ²	1	0.337	0.3371	1.68	0.198
ID ²	1	0.169	0.1688	0.84	0.361
PS ²	1	6.165	6.1653	30.69	0.000
NT ²	1	0.512	0.5122	2.55	0.113
BT ²	1	0.239	0.2394	1.19	0.277
Error	120	24.105	0.2009		
Total	134	193.084	12.2708		
R ²	87.52%				
R ² (adj)	86.06%				
R ² (pred)	84.20%				

Supplementary Table S4. Polynomial ANOVA, Printing Time vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	706262553	50447325	47.63	0.000
ORA	1	84907876	84907876	80.16	0.000
RDA	1	1211558	1211558	1.14	0.287
LT	1	94007356	94007356	88.75	0.000
ID	1	966427	966427	0.91	0.341
PS	1	11187797	11187797	10.56	0.001
NT	1	557496	557496	0.53	0.470
BT	1	4552714	4552714	4.30	0.040
ORA ²	1	88392312	88392312	83.45	0.000
RDA ²	1	1732483	1732483	1.64	0.203
LT ²	1	50056389	50056389	47.26	0.000
ID ²	1	259718	259718	0.25	0.621
PS ²	1	2618229	2618229	2.47	0.119
NT ²	1	623617	623617	0.59	0.444
BT ²	1	5107713	5107713	4.82	0.030

Error	120	127102889	1059191
Total	134	833365442	51506516
R ²	84.75%		
R ² (adj)	82.97%		
R ² (pred)	80.70%		

Supplementary Table S5. Polynomial ANOVA, sB vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	33181.4	2370.10	110.32	0.000
ORA	1	7071.2	7071.25	329.16	0.000
RDA	1	140.5	140.49	6.54	0.012
LT	1	17.0	17.03	0.79	0.375
ID	1	51.4	51.40	2.39	0.125
PS	1	2.9	2.94	0.14	0.712
NT	1	132.7	132.67	6.18	0.014
BT	1	185.6	185.62	8.64	0.004
ORA ²	1	4200.4	4200.37	195.52	0.000
RDA ²	1	731.6	731.56	34.05	0.000
LT ²	1	0.9	0.87	0.04	0.841
ID ²	1	6.7	6.65	0.31	0.579
PS ²	1	0.0	0.05	0.00	0.962
NT ²	1	135.5	135.52	6.31	0.013
BT ²	1	165.2	165.17	7.69	0.006
Error	120	2578.0	21.48		
Total	134	35759.4	2391.58		
R ²	92.79%				
R ² (adj)	91.95%				
R ² (pred)	90.88%				

Supplementary Table S6. Polynomial ANOVA, E vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	11885814	848987	111.95	0.000
ORA	1	5080771	5080771	669.96	0.000
RDA	1	38213	38213	5.04	0.027
LT	1	190282	190282	25.09	0.000
ID	1	393052	393052	51.83	0.000
PS	1	5	5	0.00	0.979
NT	1	73522	73522	9.69	0.002
BT	1	159905	159905	21.09	0.000
ORA ²	1	3475276	3475276	458.26	0.000
RDA ²	1	30196	30196	3.98	0.048
LT ²	1	170401	170401	22.47	0.000
ID ²	1	250395	250395	33.02	0.000
PS ²	1	160	160	0.02	0.885

NT ²	1	73495	73495	9.69	0.002
BT ²	1	151608	151608	19.99	0.000
Error	120	910039	7584		
Total	134	12795853	856571		
R ²	92.89%				
R ² (adj)	92.06%				
R ² (pred)	91.00%				

Supplementary Table S7. Polynomial ANOVA, Toughness vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	748.321	53.4515	103.93	0.000
ORA	1	23.937	23.9367	46.54	0.000
RDA	1	43.711	43.7110	84.99	0.000
LT	1	11.176	11.1756	21.73	0.000
ID	1	6.868	6.8677	13.35	0.000
PS	1	0.031	0.0312	0.06	0.806
NT	1	1.864	1.8638	3.62	0.059
BT	1	1.526	1.5256	2.97	0.088
ORA ²	1	3.756	3.7562	7.30	0.008
RDA ²	1	49.246	49.2461	95.75	0.000
LT ²	1	14.775	14.7748	28.73	0.000
ID ²	1	18.337	18.3366	35.65	0.000
PS ²	1	0.011	0.0105	0.02	0.886
NT ²	1	1.855	1.8547	3.61	0.060
BT ²	1	1.293	1.2927	2.51	0.115
Error	120	61.715	0.5143		
Total	134	810.036	53.9658		
R ²	92.38%				
R ² (adj)	91.49%				
R ² (pred)	90.36%				

Supplementary Table S8. Polynomial ANOVA, EPC vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	210.911	15.0651	61.28	0.000
ORA	1	2.353	2.3531	9.57	0.002
RDA	1	16.948	16.9475	68.94	0.000
LT	1	36.700	36.6996	149.28	0.000
ID	1	0.186	0.1859	0.76	0.386
PS	1	0.304	0.3037	1.24	0.269
NT	1	0.375	0.3746	1.52	0.219
BT	1	0.380	0.3801	1.55	0.216
ORA ²	1	0.169	0.1691	0.69	0.409
RDA ²	1	18.691	18.6908	76.03	0.000
LT ²	1	22.044	22.0438	89.67	0.000

ID ²	1	0.769	0.7692	3.13	0.079
PS ²	1	0.011	0.0112	0.05	0.831
NT ²	1	0.394	0.3935	1.60	0.208
BT ²	1	0.228	0.2281	0.93	0.337
Error	120	29.501	0.2458		
Total	134	240.412	15.3109		
R ²	87.73%				
R ² (adj)	86.30%				
R ² (pred)	84.47%				

Supplementary Table S9. Polynomial ANOVA, SPE vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	2.84707	0.203362	48.28	0.000
ORA	1	0.03376	0.033764	8.02	0.005
RDA	1	0.24127	0.241268	57.28	0.000
LT	1	0.58828	0.588276	139.67	0.000
ID	1	0.00287	0.002870	0.68	0.411
PS	1	0.02833	0.028326	6.73	0.011
NT	1	0.00258	0.002580	0.61	0.435
BT	1	0.01172	0.011721	2.78	0.098
ORA ²	1	0.00222	0.002217	0.53	0.470
RDA ²	1	0.27121	0.271209	64.39	0.000
LT ²	1	0.36893	0.368934	87.60	0.000
ID ²	1	0.00879	0.008793	2.09	0.151
PS ²	1	0.01175	0.011752	2.79	0.097
NT ²	1	0.00263	0.002632	0.62	0.431
BT ²	1	0.00841	0.008409	2.00	0.160
Error	120	0.50541	0.004212		
Total	134	3.35248	0.207574		
R ²	84.92%				
R ² (adj)	83.17%				
R ² (pred)	80.92%				

Supplementary Table S10. Polynomial ANOVA, SPP vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	19	0.038026	0.002001	5.03	0.000
ORA	1	0.002458	0.002458	6.18	0.014
RDA	1	0.000080	0.000080	0.20	0.655
LT	1	0.001687	0.001687	4.24	0.042
ID	1	0.000009	0.000009	0.02	0.881
PS	1	0.000295	0.000295	0.74	0.391
NT	1	0.000123	0.000123	0.31	0.580
BT	1	0.000202	0.000202	0.51	0.477
ORA ²	1	0.006625	0.006625	16.65	0.000

RDA ²	1	0.004589	0.004589	11.53	0.001
LT ²	1	0.002091	0.002091	5.25	0.024
ID ²	1	0.000001	0.000001	0.00	0.958
PS ²	1	0.000026	0.000026	0.07	0.798
NT ²	1	0.000047	0.000047	0.12	0.732
BT ²	1	0.000259	0.000259	0.65	0.422
RDA·PS	1	0.001454	0.001454	3.65	0.058
RDA·NT	1	0.000005	0.000005	0.01	0.907
RDA·BT	1	0.001478	0.001478	3.71	0.056
LT·PS	1	0.000640	0.000640	1.61	0.207
LT·NT	1	0.003008	0.003008	7.56	0.007
Error	115	0.045756	0.000398		
Total	134	0.083782	0.002399		
R ²	45.39%				
R ² (adj)	36.36%				
R ² (pred)	24.56%				

Supplementary Table S11. Polynomial ANOVA, Area2Nom vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	19	0.358513	0.018869	20.67	0.000
ORA	1	0.004644	0.004644	5.09	0.026
RDA	1	0.051852	0.051852	56.79	0.000
LT	1	0.000356	0.000356	0.39	0.534
ID	1	0.004895	0.004895	5.36	0.022
PS	1	0.010447	0.010447	11.44	0.001
NT	1	0.000284	0.000284	0.31	0.578
BT	1	0.014281	0.014281	15.64	0.000
ORA ²	1	0.003615	0.003615	3.96	0.049
RDA ²	1	0.012142	0.012142	13.30	0.000
LT ²	1	0.007029	0.007029	7.70	0.006
ID ²	1	0.003016	0.003016	3.30	0.072
PS ²	1	0.006650	0.006650	7.28	0.008
NT ²	1	0.000473	0.000473	0.52	0.473
BT ²	1	0.007852	0.007852	8.60	0.004
RDA·PS	1	0.011136	0.011136	12.20	0.001
RDA·NT	1	0.033793	0.033793	37.01	0.000
RDA·BT	1	0.028126	0.028126	30.80	0.000
LT·PS	1	0.000461	0.000461	0.51	0.479
LT·NT	1	0.001837	0.001837	2.01	0.159
Error	115	0.105001	0.000913		
Total	134	0.463514	0.019782		
R ²	77.35%				
R ² (adj)	73.60%				
R ² (pred)	69.76%				

Supplementary Table S12. Polynomial ANOVA, Volume2Nom vs ORA, RDA, LT, ID, PS, NT, BT.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	19	0.395443	0.020813	18.00	0.000
ORA	1	0.013691	0.013691	11.84	0.001
RDA	1	0.056448	0.056448	48.82	0.000
LT	1	0.000759	0.000759	0.66	0.419
ID	1	0.005175	0.005175	4.48	0.037
PS	1	0.012508	0.012508	10.82	0.001
NT	1	0.000311	0.000311	0.27	0.605
BT	1	0.015062	0.015062	13.03	0.000
ORA ²	1	0.009248	0.009248	8.00	0.006
RDA ²	1	0.015797	0.015797	13.66	0.000
LT ²	1	0.007475	0.007475	6.46	0.012
ID ²	1	0.003289	0.003289	2.84	0.094
PS ²	1	0.007889	0.007889	6.82	0.010
NT ²	1	0.000487	0.000487	0.42	0.518
BT ²	1	0.008063	0.008063	6.97	0.009
RDA·PS	1	0.013067	0.013067	11.30	0.001
RDA·NT	1	0.035003	0.035003	30.27	0.000
RDA·BT	1	0.032770	0.032770	28.34	0.000
LT·PS	1	0.000480	0.000480	0.42	0.521
LT·NT	1	0.002816	0.002816	2.44	0.121
Error	115	0.132976	0.001156		
Total	134	0.528419	0.021969		
R ²	74.84%				
R ² (adj)	70.68%				
R ² (pred)	66.52%				

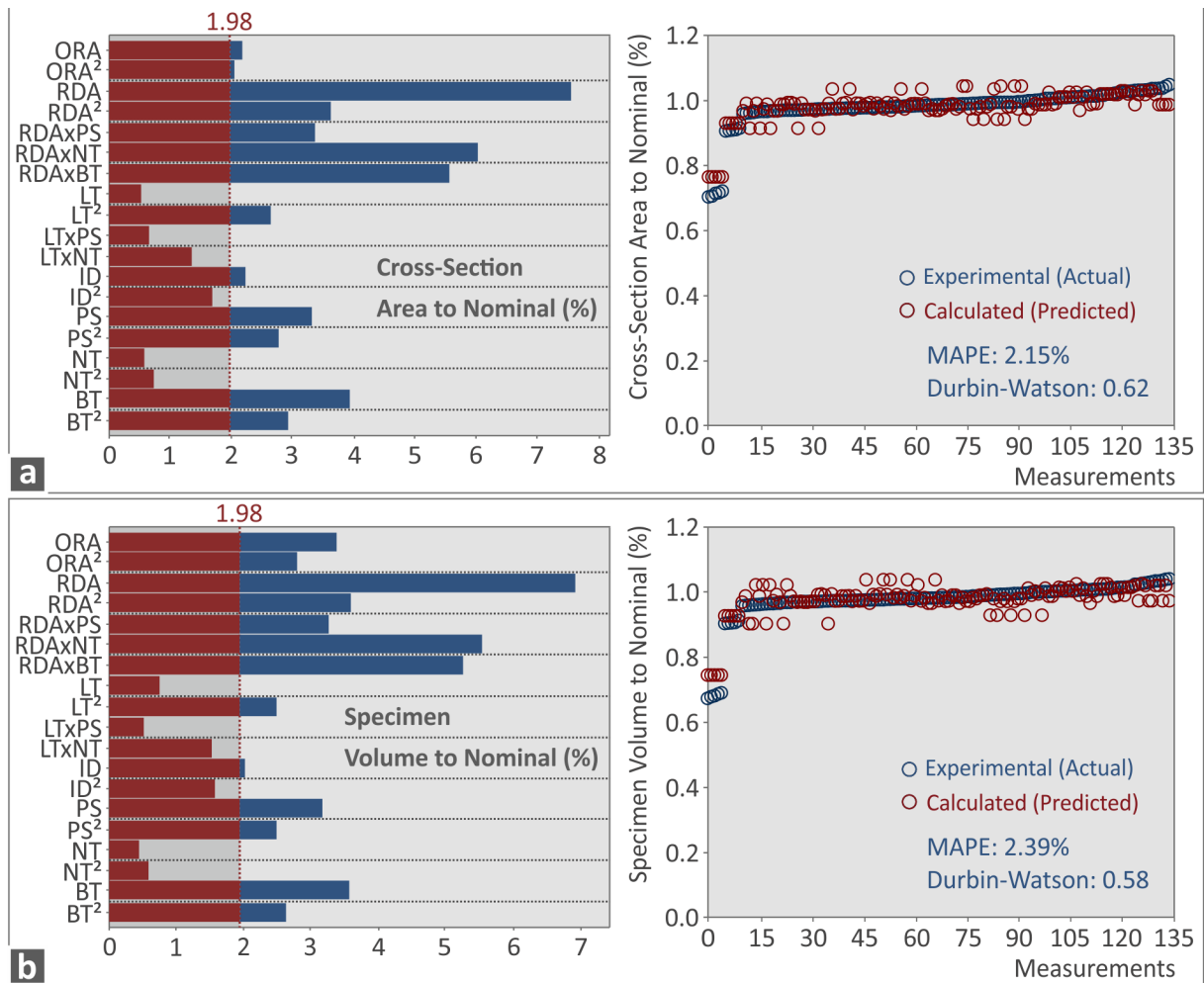


Figure S7. Pareto chart for (a) the area to nominal (%) and (b) the volume to nominal (%) vs the control parameters of the work, showing the parameters crossing the 1.98 threshold (statistically significant parameters). On the right side the actual vs the calculated values are shown.

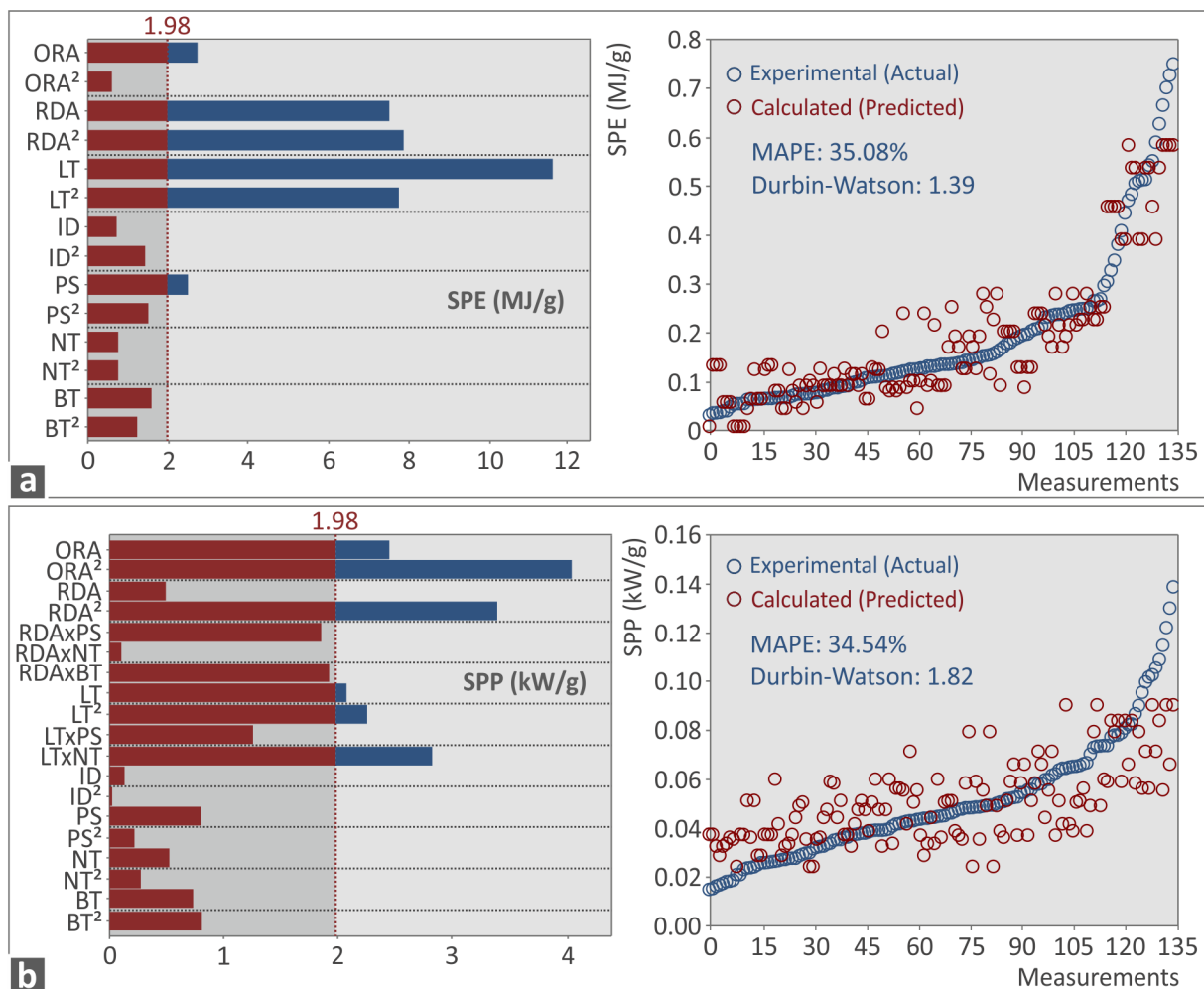


Figure S8. Pareto chart for (a) the SPE (MJ/g) and (b) the SPP (kW/g) vs the control parameters of the work, showing the parameters crossing the 1.98 threshold (statistically significant parameters). On the right side the actual vs the calculated values are shown.

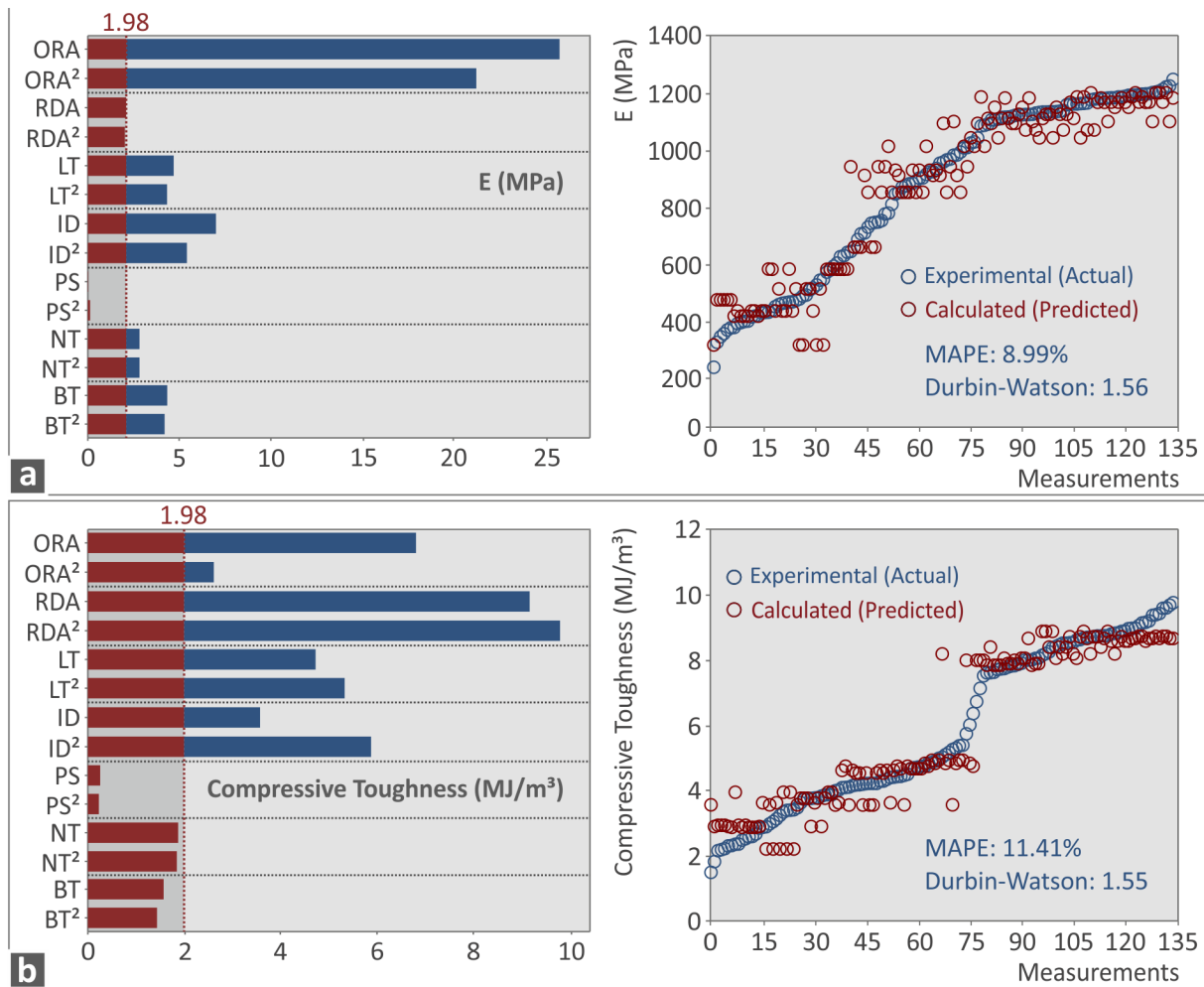


Figure S9. Pareto chart for (a) the compression modulus of elasticity (MPa) and (b) the compressive toughness (MJ/m³) vs the control parameters of the work, showing the parameters crossing the 1.98 threshold (statistically significant parameters). On the right side the actual vs the calculated values are shown.

Confirmation runs

Supplementary Table S13. Measured Printing Time and Weight for each experimental run and five replicas per run for the Confirmation Runs.

A/A	Run	Weight (g)	Printing Time (sec)	sB [MPa]	E [MPa]	Toughness [MJ/m ³]
1	28	9.50	10465	81.91	1328.81	9.71
2		9.62	11202	79.18	1358.29	9.83
3		9.47	10650	79.99	1438.34	10.88
4		9.64	11546	83.70	1329.99	9.86
5		9.37	10410	78.84	1389.72	10.89
6	29	7.46	1067	42.17	1001.28	4.79
7		7.59	1343	42.34	1097.37	4.66
8		7.06	1065	44.27	1080.36	4.80
9		7.13	1031	41.45	1105.32	4.82
10		7.11	1284	42.08	1058.26	4.60
	Min:	7.06	1031	41.45	1001.28	4.60
	Max:	9.64	11546	83.70	1438.34	10.89
	Average:	8.40	6006.30	61.59	1218.77	7.48

Supplementary Table S14. Measured EPC, SPE, SPP, Compressive Strength, Compressive Modulus of Elasticity, Compressive Toughness for each experimental run and five replicas per run for the Confirmation Runs.

A/A	Run	EPC (MJ)	SPE (MJ/g)	SPP (kW/g)	Area 2 Nom [%]	Volume 2 Nom [%]
1	28	3.996	0.421	0.040	0.92	0.91
2		4.464	0.464	0.041	0.92	0.90
3		3.816	0.403	0.038	0.92	0.91
4		4.392	0.456	0.039	0.91	0.92
5		3.492	0.373	0.036	0.91	0.92
6	29	0.612	0.082	0.077	1.07	0.88
7		0.504	0.066	0.049	1.07	0.87
8		0.468	0.066	0.062	1.08	0.88
9		0.432	0.061	0.059	1.07	0.88
10		0.576	0.081	0.063	1.06	0.88
	Min:	0.432	0.061	0.036	0.91	0.87
	Max:	4.464	0.464	0.077	1.08	0.92
	Average:	2.275	0.247	0.051	0.99	0.89