**Table 1.** Summary of test data.

|  |  |
| --- | --- |
| Factors | Levels |
| Number of tasks (*N*) | 50/100/150 |
| Number of machines (*M*) | 5/10/20 |
| Number of service engineers (*W*) | 5/10/15 |
| Number of types of spare parts (*T*) | 5/10 |
| Weight of tasks (*WT*i) | Uniform distribution [1,3] |
| Processing time (*Ptm*) | Uniform distribution [10,50] |
| Replacement time (*Rt*) | Uniform distribution [30,90] |
| Incidental outsourcing costs (*Ct*) | Uniform distribution [200,600] |
| Transfer time between the firm and each demand site (*TFi*) | Uniform distribution [20,120] |

Table 2. Coverage metric comparisons between PPAS and NSGA-II, MOEA/D, NNIA, RIPG, MMOIG, MNNIA.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Instances  *N*×*M*×*W* |  | *C*(PPAS, NSGA-II) | *C*(NSGA-II, PPAS) | *C*(PPAS, MOEA/D) | *C*(MOEA/D, PPAS) | *C*(PPAS, NNIA) | *C*(NNIA, PPAS) | *C*(PPAS, RIPG) | *C*(RIPG, PPAS) | *C*(PPAS, MMOIG) | *C*(MMOIG, PPAS) | *C*(PPAS, MNNIA) | *C*(MNNIA, PPAS) |
| 50×5×5 |  | **0.899** | 0.053 | **0.939** | 0.019 | **0.625** | 0.087 | **0.855** | 0.056 | **0.909** | 0.051 | **0.547** | 0.166 |
| 50×5×10 |  | **0.898** | 0.082 | **0.901** | 0.074 | **0.549** | 0.222 | **0.846** | 0.074 | **0.879** | 0.088 | **0.475** | 0.299 |
| 50×5×15 |  | **0.926** | 0.012 | **0.916** | 0.024 | **0.677** | 0.145 | **0.818** | 0.057 | **0.901** | 0.027 | **0.645** | 0.119 |
| 50×10×5 |  | **0.895** | 0.025 | **0.888** | 0.054 | **0.724** | 0.145 | **0.806** | 0.079 | **0.849** | 0.038 | **0.639** | 0.177 |
| 50×10×10 |  | **0.917** | 0.038 | **0.908** | 0.046 | **0.705** | 0.102 | **0.867** | 0.038 | **0.864** | 0.045 | **0.696** | 0.126 |
| 50×10×15 |  | **0.904** | 0.045 | **0.933** | 0.027 | **0.672** | 0.085 | **0.817** | 0.031 | **0.881** | 0.019 | **0.798** | 0.064 |
| 50×20×5 |  | **0.923** | 0.054 | **0.920** | 0.000 | **0.769** | 0.065 | **0.795** | 0.054 | **0.868** | 0.045 | **0.744** | 0.110 |
| 50×20×10 |  | **0.957** | 0.011 | **0.907** | 0.000 | **0.902** | 0.025 | **0.850** | 0.036 | **0.885** | 0.038 | **0.861** | 0.032 |
| 50×20×15 |  | **0.912** | 0.032 | **0.899** | 0.045 | **0.805** | 0.077 | **0.684** | 0.050 | **0.890** | 0.045 | **0.806** | 0.067 |
| 100×5×5 |  | **0.965** | 0.007 | **0.958** | 0.006 | **0.958** | 0.000 | **0.803** | 0.040 | **0.949** | 0.010 | **0.954** | 0.004 |
| 100×5×10 |  | **0.956** | 0.017 | **0.968** | 0.011 | **0.939** | 0.019 | **0.801** | 0.040 | **0.929** | 0.010 | **0.955** | 0.024 |
| 100×5×15 |  | **0.975** | 0.007 | **0.975** | 0.000 | **0.980** | 0.000 | **0.890** | 0.011 | **0.924** | 0.010 | **0.954** | 0.009 |
| 100×10×5 |  | **0.968** | 0.006 | **0.965** | 0.003 | **0.962** | 0.013 | **0.813** | 0.033 | **0.953** | 0.025 | **0.927** | 0.032 |
| 100×10×10 |  | **0.956** | 0.005 | **0.947** | 0.011 | **0.955** | 0.009 | **0.740** | 0.013 | **0.920** | 0.018 | **0.924** | 0.005 |
| 100×10×15 |  | **0.957** | 0.016 | **0.936** | 0.016 | **0.949** | 0.028 | **0.655** | 0.044 | **0.933** | 0.028 | **0.927** | 0.040 |
| 100×20×5 |  | **0.958** | 0.008 | **0.942** | 0.008 | **0.948** | 0.008 | **0.802** | 0.038 | **0.942** | 0.008 | **0.962** | 0.008 |
| 100×20×10 |  | **0.928** | 0.005 | **0.969** | 0.008 | **0.939** | 0.016 | **0.745** | 0.051 | **0.953** | 0.013 | **0.943** | 0.019 |
| 100×20×15 |  | **0.953** | 0.000 | **0.946** | 0.013 | **0.957** | 0.018 | **0.735** | 0.012 | **0.938** | 0.006 | **0.995** | 0.000 |
| 200×5×5 |  | **0.997** | 0.000 | **0.977** | 0.002 | **0.990** | 0.009 | **0.777** | 0.023 | **0.980** | 0.015 | **0.974** | 0.012 |
| 200×5×10 |  | **0.983** | 0.019 | **0.962** | 0.013 | **0.969** | 0.017 | **0.592** | 0.046 | **0.940** | 0.017 | **0.958** | 0.024 |
| 200×5×15 |  | **0.992** | 0.000 | **0.989** | 0.000 | **0.986** | 0.000 | **0.626** | 0.036 | **0.972** | 0.000 | **0.971** | 0.004 |
| 200×10×5 |  | **0.982** | 0.008 | **0.960** | 0.000 | **0.983** | 0.000 | **0.842** | 0.008 | **0.973** | 0.000 | **0.953** | 0.002 |
| 200×10×10 |  | **0.996** | 0.000 | **0.983** | 0.007 | **0.975** | 0.004 | **0.772** | 0.007 | **0.971** | 0.004 | **0.989** | 0.000 |
| 200×10×15 |  | **0.972** | 0.005 | **0.985** | 0.000 | **0.978** | 0.004 | **0.617** | 0.029 | **0.984** | 0.005 | **0.976** | 0.005 |
| 200×20×5 |  | **0.986** | 0.006 | **0.982** | 0.000 | **0.984** | 0.006 | **0.738** | 0.020 | **0.995** | 0.000 | **0.969** | 0.000 |
| 200×20×10 |  | **0.987** | 0.000 | **0.994** | 0.000 | **0.994** | 0.000 | **0.722** | 0.024 | **0.990** | 0.000 | **0.993** | 0.000 |
| 200×20×15 |  | **0.984** | 0.000 | **0.975** | 0.010 | **0.980** | 0.005 | **0.575** | 0.040 | **0.964** | 0.010 | **0.958** | 0.026 |
| Average |  | **0.953** | 0.017 | **0.949** | 0.015 | **0.883** | 0.041 | **0.762** | 0.037 | **0.931** | 0.021 | **0.870** | 0.051 |

Table 3. Performance comparison of PPAS, NSGA-II, NNIA, MOEA/D, RIPG, MMOIG and MNNIA.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Instances |  | *Rnd* | | | | | | |  | *HV* | | | | | | |  | *tmax* | |
| *N*×*M*×*W* |  | PPAS | NSGA-II | MOEA/D | NNIA | RIPG | MMOIG | MNNIA |  | PPAS | NSGA-II | MOEA/D | NNIA | RIPG | MMOIG | MNNIA |  | PPAS | Others |
| 50×5×5 |  | **0.734** | 0.026 | 0.021 | 0.252 | 0.075 | 0.027 | 0.383 |  | **1.370** | 1.311 | 1.259 | 1.359 | 1.135 | 1.266 | 1.362 |  | **0.500** | 10 |
| 50×5×10 |  | **0.617** | 0.009 | 0.015 | 0.310 | 0.077 | 0.035 | 0.394 |  | **1.368** | 1.320 | 1.287 | 1.363 | 1.167 | 1.278 | 1.364 |  | **0.618** | 10 |
| 50×5×15 |  | **0.756** | 0.005 | 0.021 | 0.222 | 0.101 | 0.046 | 0.248 |  | **1.373** | 1.321 | 1.282 | 1.363 | 1.154 | 1.276 | 1.361 |  | **0.384** | 10 |
| 50×10×5 |  | **0.709** | 0.008 | 0.047 | 0.179 | 0.111 | 0.037 | 0.259 |  | **1.378** | 1.318 | 1.278 | 1.364 | 1.161 | 1.281 | 1.368 |  | **0.399** | 10 |
| 50×10×10 |  | **0.771** | 0.000 | 0.036 | 0.198 | 0.087 | 0.054 | 0.192 |  | **1.371** | 1.303 | 1.273 | 1.358 | 1.132 | 1.266 | 1.358 |  | **0.558** | 10 |
| 50×10×15 |  | **0.841** | 0.041 | 0.031 | 0.245 | 0.090 | 0.028 | 0.128 |  | **1.357** | 1.285 | 1.228 | 1.343 | 1.026 | 1.228 | 1.341 |  | **0.316** | 10 |
| 50×20×5 |  | **0.805** | 0.027 | 0.007 | 0.170 | 0.123 | 0.080 | 0.142 |  | **1.398** | 1.344 | 1.326 | 1.381 | 1.198 | 1.326 | 1.380 |  | **0.458** | 10 |
| 50×20×10 |  | **0.885** | 0.014 | 0.053 | 0.076 | 0.112 | 0.059 | 0.086 |  | **1.399** | 1.329 | 1.319 | 1.373 | 1.160 | 1.319 | 1.372 |  | **0.678** | 10 |
| 50×20×15 |  | **0.880** | 0.020 | 0.046 | 0.145 | 0.116 | 0.045 | 0.084 |  | **1.367** | 1.283 | 1.261 | 1.341 | 0.937 | 1.260 | 1.340 |  | **0.445** | 10 |
| 100×5×5 |  | **0.947** | 0.008 | 0.020 | 0.024 | 0.162 | 0.024 | 0.017 |  | **1.414** | 1.345 | 1.319 | 1.386 | 1.194 | 1.325 | 1.383 |  | **1.092** | 20 |
| 100×5×10 |  | **0.932** | 0.020 | 0.003 | 0.020 | 0.137 | 0.026 | 0.036 |  | **1.414** | 1.351 | 1.329 | 1.384 | 1.200 | 1.329 | 1.383 |  | **0.868** | 20 |
| 100×5×15 |  | **0.968** | 0.013 | 0.020 | 0.011 | 0.070 | 0.046 | 0.026 |  | **1.388** | 1.261 | 1.217 | 1.329 | 0.783 | 1.218 | 1.330 |  | **0.832** | 20 |
| 100×10×5 |  | **0.921** | 0.010 | 0.007 | 0.006 | 0.121 | 0.018 | 0.050 |  | **1.404** | 1.311 | 1.289 | 1.361 | 1.052 | 1.285 | 1.368 |  | **1.072** | 20 |
| 100×10×10 |  | **0.963** | 0.009 | 0.018 | 0.002 | 0.128 | 0.038 | 0.058 |  | **1.400** | 1.282 | 1.253 | 1.337 | 0.904 | 1.251 | 1.341 |  | **0.985** | 20 |
| 100×10×15 |  | **0.928** | 0.017 | 0.012 | 0.010 | 0.256 | 0.030 | 0.048 |  | **1.406** | 1.317 | 1.299 | 1.359 | 1.006 | 1.289 | 1.359 |  | **1.638** | 20 |
| 100×20×5 |  | **0.954** | 0.000 | 0.048 | 0.022 | 0.178 | 0.034 | 0.024 |  | **1.418** | 1.332 | 1.325 | 1.365 | 1.062 | 1.324 | 1.363 |  | **0.933** | 20 |
| 100×20×10 |  | **0.924** | 0.021 | 0.010 | 0.024 | 0.182 | 0.014 | 0.037 |  | **1.411** | 1.318 | 1.303 | 1.354 | 1.068 | 1.309 | 1.352 |  | **1.433** | 20 |
| 100×20×15 |  | **0.970** | 0.041 | 0.041 | 0.032 | 0.195 | 0.038 | 0.000 |  | **1.400** | 1.254 | 1.227 | 1.313 | 0.784 | 1.235 | 1.301 |  | **0.631** | 20 |
| 200×5×5 |  | **0.946** | 0.000 | 0.011 | 0.008 | 0.121 | 0.007 | 0.017 |  | **1.413** | 1.286 | 1.264 | 1.330 | 0.959 | 1.268 | 1.338 |  | **2.998** | 40 |
| 200×5×10 |  | **0.928** | 0.003 | 0.006 | 0.005 | 0.295 | 0.043 | 0.027 |  | **1.416** | 1.302 | 1.280 | 1.345 | 0.958 | 1.288 | 1.348 |  | **2.677** | 40 |
| 200×5×15 |  | **0.961** | 0.008 | 0.003 | 0.006 | 0.334 | 0.013 | 0.016 |  | **1.417** | 1.302 | 1.275 | 1.337 | 0.879 | 1.274 | 1.341 |  | **1.588** | 40 |
| 200×10×5 |  | **0.982** | 0.011 | 0.004 | 0.007 | 0.085 | 0.004 | 0.044 |  | **1.425** | 1.317 | 1.301 | 1.347 | 0.982 | 1.315 | 1.360 |  | **2.640** | 40 |
| 200×10×10 |  | **0.982** | 0.000 | 0.013 | 0.016 | 0.203 | 0.015 | 0.005 |  | **1.414** | 1.257 | 1.233 | 1.303 | 0.749 | 1.231 | 1.306 |  | **3.480** | 40 |
| 200×10×15 |  | **0.962** | 0.018 | 0.004 | 0.019 | 0.383 | 0.005 | 0.014 |  | **1.419** | 1.283 | 1.263 | 1.325 | 0.805 | 1.271 | 1.322 |  | **2.220** | 40 |
| 200×20×5 |  | **0.974** | 0.006 | 0.000 | 0.005 | 0.208 | 0.000 | 0.031 |  | **1.426** | 1.320 | 1.306 | 1.347 | 0.932 | 1.313 | 1.333 |  | **3.076** | 40 |
| 200×20×10 |  | **0.976** | 0.007 | 0.000 | 0.006 | 0.278 | 0.005 | 0.000 |  | **1.431** | 1.345 | 1.339 | 1.368 | 1.084 | 1.339 | 1.365 |  | **2.531** | 40 |
| 200×20×15 |  | **0.940** | 0.003 | 0.012 | 0.007 | 0.382 | 0.017 | 0.031 |  | **1.431** | 1.355 | 1.345 | 1.370 | 1.110 | 1.346 | 1.370 |  | **4.510** | 40 |
| Average |  | **0.895** | 0.013 | 0.019 | 0.075 | 0.171 | 0.029 | 0.089 |  | **1.401** | 1.309 | 1.284 | 1.352 | 1.022 | 1.286 | 1.352 |  | **1.465** | 23.333 |

Table 4. Performance comparison between the joint scheduling and the separate optimization.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Instances |  | *C* | |  | *Rnd* | |  | *HV* | |  | Instances |  | *C* | |  | *Rnd* | |  | *HV* | |
| *N*×*M*×*W* |  | *C*(mode1, mode2) | *C*(mode2, mode1) |  | mode1 | mode2 |  | mode1 | mode2 |  | *N*×*M*×*W* |  | *C*(mode1, mode2) | *C*(mode2, mode1) |  | mode1 | mode2 |  | mode1 | mode2 |
| 50×5×5 |  | **0.591** | 0.049 |  | **0.951** | 0.409 |  | **1.217** | 1.168 |  | 100×10×15 |  | **0.533** | 0.013 |  | **0.988** | 0.467 |  | **1.209** | 1.187 |
| 50×5×10 |  | **0.477** | 0.031 |  | **0.969** | 0.523 |  | **1.210** | 1.182 |  | 100×20×5 |  | **0.307** | 0.015 |  | **0.985** | 0.693 |  | **1.190** | 1.165 |
| 50×5×15 |  | **0.388** | 0.085 |  | **0.915** | 0.612 |  | **1.212** | 1.200 |  | 100×20×10 |  | **0.350** | 0.092 |  | **0.908** | 0.650 |  | **1.178** | 1.156 |
| 50×10×5 |  | **0.432** | 0.103 |  | **0.897** | 0.568 |  | **1.192** | 1.165 |  | 100×20×15 |  | **0.539** | 0.008 |  | **0.992** | 0.461 |  | **1.176** | 1.144 |
| 50×10×10 |  | **0.705** | 0.129 |  | **0.871** | 0.295 |  | **1.206** | 1.178 |  | 200×5×5 |  | **0.310** | 0.202 |  | **0.798** | 0.690 |  | **1.205** | 1.202 |
| 50×10×15 |  | **0.194** | 0.056 |  | **0.944** | 0.806 |  | **1.197** | 1.181 |  | 200×5×10 |  | **0.208** | 0.097 |  | **0.903** | 0.792 |  | **1.191** | 1.184 |
| 50×20×5 |  | **0.470** | 0.099 |  | **0.901** | 0.530 |  | **1.144** | 1.113 |  | 200×5×15 |  | **0.452** | 0.012 |  | **0.988** | 0.548 |  | **1.205** | 1.180 |
| 50×20×10 |  | **0.303** | 0.071 |  | **0.929** | 0.697 |  | **1.195** | 1.169 |  | 200×10×5 |  | **0.398** | 0.155 |  | **0.845** | 0.602 |  | **1.231** | 1.209 |
| 50×20×15 |  | **0.182** | 0.038 |  | **0.962** | 0.818 |  | **1.159** | 1.146 |  | 200×10×10 |  | **0.481** | 0.016 |  | **0.984** | 0.519 |  | **1.187** | 1.166 |
| 100×5×5 |  | **0.418** | 0.066 |  | **0.934** | 0.582 |  | **1.228** | 1.206 |  | 200×10×15 |  | **0.270** | 0.111 |  | **0.889** | 0.730 |  | **1.197** | 1.183 |
| 100×5×10 |  | **0.289** | 0.072 |  | **0.928** | 0.711 |  | **1.199** | 1.193 |  | 200×20×5 |  | **0.553** | 0.028 |  | **0.972** | 0.447 |  | **1.210** | 1.184 |
| 100×5×15 |  | **0.382** | 0.024 |  | **0.976** | 0.618 |  | **1.205** | 1.180 |  | 200×20×10 |  | **0.339** | 0.049 |  | **0.951** | 0.661 |  | **1.199** | 1.168 |
| 100×10×5 |  | **0.591** | 0.012 |  | **0.988** | 0.409 |  | **1.204** | 1.163 |  | 200×20×15 |  | **0.397** | 0.047 |  | **0.953** | 0.603 |  | **1.230** | 1.204 |
| 100×10×10 |  | **0.466** | 0.095 |  | **0.905** | 0.534 |  | **1.207** | 1.181 |  | Average |  | **0.408** | 0.066 |  | **0.934** | 0.592 |  | **1.199** | 1.176 |