760-Heuristics-Assignment

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1 Question 1

Neighbors of the current solution can be found by swapping one pot in any crucible with a pot in any other crucible. This can be formally defined as following:

$N(\mathbf{x}) = \{\mathbf{y}(\mathbf{x}, k, l, m, n), k = 1, 2, 3, ..., 16, l = k + 1, k + 2, k + 3, ...17, m = 1, 2, 3, n = 1, 2, 3\}$ where

$$\mathbf{y}(\mathbf{x}, k, l, m, n) = (y_{1,1}, y_{1,2}, y_{1,3}; y_{2,1}y_{2,2}y_{2,3}; ...y_{c,j}), y_{c,j} = \begin{cases} x_{l,n} & \text{if } c = k, j = m \\ x_{k,m} & \text{if } c = l, j = n \\ x_{c,j} & \text{otherwise} \end{cases}$$

2 Question 2

Algorithm 1 Sweep x

Let x be the current configuration
Let I be the intermediate values
Let $I_c = g(\overline{Al}[x_c], \overline{Fe}[x_c]\overline{Si}[x_c])$
for k=1...16; m=1...3; l=k...17; n=1..3 **do**
  $y = y(x, k, l, m, n)$
  $d = g(\overline{Al}[y_k], \overline{Fe}[y_k]\overline{Si}[y_k]) + g(\overline{Al}[y_l], \overline{Fe}[y_l]\overline{Si}[y_l]) - I_k - I_l$
  if $d > 0$ **then**
    $x := y$
    $I_k = g(\overline{Al}[y_k], \overline{Fe}[y_k]\overline{Si}[y_k])$
    $I_l = g(a(\overline{Al}[y_l], \overline{Fe}[y_l]\overline{Si}[y_l]))$
  end if
end for

3 Question 3

3.1 Question 3A

See Appendix A for code.

3.2 Question 3B

See Appendix A for code.

3.3 Question 3C

See Appendix A for plot.

3.4 Question 3D

See Appendix A for plot.

3.5 Question 3E

See Appendix A for code and plots. Best solution found using repeated next ascents with $n = 200$.

```
 1 [27  4 45 ] 99.261 %Al, 0.274 %Fe, 0.110 %Si, $41.53, spread = 41
 2 [ 8 13 37 ] 99.508 %Al, 0.154 %Fe, 0.153 %Si, $48.71, spread = 29
 3 [50 40 30 ] 99.504 %Al, 0.143 %Fe, 0.238 %Si, $48.71, spread = 20
 4 [17 51 15 ] 99.268 %Al, 0.162 %Fe, 0.386 %Si, $41.53, spread = 36
 5 [24 23 46 ] 99.512 %Al, 0.053 %Fe, 0.180 %Si, $48.71, spread = 23
 6 [28 12 32 ] 99.358 %Al, 0.096 %Fe, 0.348 %Si, $44.53, spread = 20
 7 [18  3 42 ] 99.760 %Al, 0.040 %Fe, 0.139 %Si, $57.35, spread = 39
 8 [19 41 20 ] 99.262 %Al, 0.212 %Fe, 0.249 %Si, $41.53, spread = 22
 9 [11 25  5 ] 99.353 %Al, 0.185 %Fe, 0.325 %Si, $44.53, spread = 20
10 [ 9  6 21 ] 99.504 %Al, 0.139 %Fe, 0.253 %Si, $48.71, spread = 15
11 [ 7 36 26 ] 99.506 %Al, 0.098 %Fe, 0.268 %Si, $48.71, spread = 29
12 [47 39  2 ] 99.503 %Al, 0.114 %Fe, 0.270 %Si, $48.71, spread = 45
13 [22 33 10 ] 99.356 %Al, 0.187 %Fe, 0.219 %Si, $44.53, spread = 23
14 [34 29 38 ] 99.361 %Al, 0.209 %Fe, 0.241 %Si, $44.53, spread =  9
15 [14 43 49 ] 99.254 %Al, 0.224 %Fe, 0.307 %Si, $41.53, spread = 35
16 [ 1 35 31 ] 99.350 %Al, 0.075 %Fe, 0.336 %Si, $44.53, spread = 34
17 [48 44 16 ] 99.515 %Al, 0.143 %Fe, 0.241 %Si, $48.71, spread = 32
                                          Sum = $787.09, MxSprd = 45
```

Best solution found using repeated steepest ascents with $n = 200$.

```
 1 [ 1 48 15 ] 99.256 %Al, 0.121 %Fe, 0.300 %Si, $41.53, spread = 47
 2 [29 36 10 ] 99.369 %Al, 0.216 %Fe, 0.272 %Si, $44.53, spread = 26
 3 [33  6 34 ] 99.268 %Al, 0.253 %Fe, 0.272 %Si, $41.53, spread = 28
 4 [42 16 49 ] 99.502 %Al, 0.161 %Fe, 0.163 %Si, $48.71, spread = 33
```

```
 5 [43 24 39 ] 99.508 %Al, 0.067 %Fe, 0.243 %Si, $48.71, spread = 19
 6 [47  8  5 ] 99.366 %Al, 0.188 %Fe, 0.317 %Si, $44.53, spread = 42
 7 [ 4 26 19 ] 99.253 %Al, 0.243 %Fe, 0.283 %Si, $41.53, spread = 22
 8 [31 28 46 ] 99.365 %Al, 0.139 %Fe, 0.196 %Si, $44.53, spread = 18
 9 [ 3 11 23 ] 99.502 %Al, 0.058 %Fe, 0.246 %Si, $48.71, spread = 20
10 [32 27 35 ] 99.501 %Al, 0.087 %Fe, 0.224 %Si, $48.71, spread =  8
11 [22 40 51 ] 99.353 %Al, 0.122 %Fe, 0.349 %Si, $44.53, spread = 29
12 [13 38  2 ] 99.504 %Al, 0.177 %Fe, 0.160 %Si, $48.71, spread = 36
13 [50 25 37 ] 99.500 %Al, 0.188 %Fe, 0.231 %Si, $48.71, spread = 25
14 [20 30 17 ] 99.522 %Al, 0.111 %Fe, 0.277 %Si, $48.71, spread = 13
15 [ 9 18 44 ] 99.750 %Al, 0.037 %Fe, 0.099 %Si, $57.35, spread = 35
16 [45 41 12 ] 99.258 %Al, 0.171 %Fe, 0.284 %Si, $41.53, spread = 33
17 [21  7 14 ] 99.360 %Al, 0.168 %Fe, 0.347 %Si, $44.53, spread = 14
                                          Sum = $787.09, MxSprd = 47
```

4 Quesion 4

There does not seem to be a significant difference in the objective value for next and steepest ascent. Steepest ascent also took far longer to converge on each local optimum. This means that fastest ascent is better than steepest ascent; however, this conclusion is from limited information so it not conclusive evidence.

5 Question 5

(a) You would expect the problem's objective function to have lots of plateus because the objective function is not continuous. This means there will be lots of cases where two pots are swapped and the quality, and thus value, will remain constant.
(b)

6 Question 6

$$g''(\overline{Al}, \overline{Fe}, \overline{Si}, x_{c1}, x_{c2}, x_{c3}, s) = \begin{cases} g(\overline{Al}, \overline{Fe}, \overline{Si}) - 10000 * (s_c - s) & \text{if } s_c > s \\ g(\overline{Al}, \overline{Fe}, \overline{Si}) \text{otherwise} \end{cases}$$

where $s_c = \max(x_{c1}, x_{c2}, x_{c3}) - \min(x_{c1}, x_{c2}, x_{c3})$

6.1 Task 6

See Appendix A for code.

6.1.1 Max Spread = 6

```
 1 [38 34 40 ] 99.371 %Al, 0.241 %Fe, 0.163 %Si, $44.53, spread =  6
 2 [17 13 19 ] 99.270 %Al, 0.297 %Fe, 0.234 %Si, $41.53, spread =  6
 3 [35 36 39 ] 99.615 %Al, 0.043 %Fe, 0.196 %Si, $48.71, spread =  4
 4 [ 6  8 10 ] 99.352 %Al, 0.257 %Fe, 0.275 %Si, $44.53, spread =  4
 5 [30 32 27 ] 99.558 %Al, 0.093 %Fe, 0.170 %Si, $48.71, spread =  5
 6 [37 42 41 ] 99.501 %Al, 0.115 %Fe, 0.198 %Si, $48.71, spread =  5
 7 [24 22 21 ] 99.532 %Al, 0.037 %Fe, 0.276 %Si, $48.71, spread =  3
 8 [33 29 28 ] 99.256 %Al, 0.151 %Fe, 0.303 %Si, $41.53, spread =  5
 9 [11 14  9 ] 99.381 %Al, 0.080 %Fe, 0.297 %Si, $44.53, spread =  5
10 [ 5  7  3 ] 99.512 %Al, 0.188 %Fe, 0.212 %Si, $48.71, spread =  4
11 [46 47 43 ] 99.359 %Al, 0.172 %Fe, 0.315 %Si, $44.53, spread =  4
12 [26 25 31 ] 99.393 %Al, 0.138 %Fe, 0.325 %Si, $44.53, spread =  6
13 [49 48 44 ] 99.511 %Al, 0.169 %Fe, 0.145 %Si, $48.71, spread =  5
14 [20 18 23 ] 99.544 %Al, 0.057 %Fe, 0.220 %Si, $48.71, spread =  5
15 [15 16 12 ] 99.369 %Al, 0.127 %Fe, 0.302 %Si, $44.53, spread =  4
16 [ 2  4  1 ] 99.356 %Al, 0.144 %Fe, 0.280 %Si, $44.53, spread =  3
17 [50 51 45 ] 99.256 %Al, 0.198 %Fe, 0.351 %Si, $41.53, spread =  6
                                          Sum = $777.27, MxSprd =  6
```

6.1.2 Max Spread = 8

```
 1 [15 13 11 ] 99.255 %Al, 0.157 %Fe, 0.277 %Si, $41.53, spread =  4
 2 [ 2  1  4 ] 99.356 %Al, 0.144 %Fe, 0.280 %Si, $44.53, spread =  3
 3 [46 49 51 ] 99.399 %Al, 0.152 %Fe, 0.259 %Si, $44.53, spread =  5
 4 [26 19 24 ] 99.355 %Al, 0.140 %Fe, 0.305 %Si, $44.53, spread =  7
 5 [32 29 36 ] 99.509 %Al, 0.087 %Fe, 0.197 %Si, $48.71, spread =  7
 6 [34 35 33 ] 99.358 %Al, 0.156 %Fe, 0.278 %Si, $44.53, spread =  2
 7 [ 8  3 10 ] 99.527 %Al, 0.176 %Fe, 0.194 %Si, $48.71, spread =  7
 8 [48 50 44 ] 99.544 %Al, 0.129 %Fe, 0.241 %Si, $48.71, spread =  6
 9 [14  6  7 ] 99.253 %Al, 0.249 %Fe, 0.360 %Si, $41.53, spread =  8
10 [16 18 17 ] 99.542 %Al, 0.132 %Fe, 0.258 %Si, $48.71, spread =  2
11 [30 27 23 ] 99.505 %Al, 0.105 %Fe, 0.199 %Si, $48.71, spread =  7
12 [20 22 21 ] 99.516 %Al, 0.060 %Fe, 0.277 %Si, $48.71, spread =  2
13 [43 45 38 ] 99.350 %Al, 0.226 %Fe, 0.125 %Si, $44.53, spread =  7
14 [ 9  5 12 ] 99.510 %Al, 0.106 %Fe, 0.258 %Si, $48.71, spread =  7
15 [40 39 47 ] 99.378 %Al, 0.169 %Fe, 0.269 %Si, $44.53, spread =  8
16 [28 25 31 ] 99.278 %Al, 0.204 %Fe, 0.285 %Si, $41.53, spread =  6
17 [42 41 37 ] 99.501 %Al, 0.115 %Fe, 0.198 %Si, $48.71, spread =  5
                                          Sum = $781.45, MxSprd =  8
```

6.1.3 Max Spread = 11

```
 1 [40 49 51 ] 99.301 %Al, 0.205 %Fe, 0.295 %Si, $41.53, spread = 11
 2 [35 33 34 ] 99.358 %Al, 0.156 %Fe, 0.278 %Si, $44.53, spread =  2
 3 [ 5  3  7 ] 99.512 %Al, 0.188 %Fe, 0.212 %Si, $48.71, spread =  4
```

```
 4 [29 31 28 ] 99.257 %Al, 0.160 %Fe, 0.310 %Si, $41.53, spread =  3
 5 [ 4  6  9 ] 99.386 %Al, 0.217 %Fe, 0.204 %Si, $44.53, spread =  5
 6 [36 32 26 ] 99.524 %Al, 0.048 %Fe, 0.266 %Si, $48.71, spread = 10
 7 [39 44 47 ] 99.500 %Al, 0.124 %Fe, 0.270 %Si, $48.71, spread =  8
 8 [25 18 16 ] 99.527 %Al, 0.153 %Fe, 0.256 %Si, $48.71, spread =  9
 9 [41 50 48 ] 99.351 %Al, 0.151 %Fe, 0.329 %Si, $44.53, spread =  9
10 [14 22 24 ] 99.362 %Al, 0.083 %Fe, 0.335 %Si, $44.53, spread = 10
11 [13 23 19 ] 99.251 %Al, 0.258 %Fe, 0.213 %Si, $41.53, spread = 10
12 [30 27 20 ] 99.530 %Al, 0.104 %Fe, 0.212 %Si, $48.71, spread = 10
13 [46 42 45 ] 99.502 %Al, 0.140 %Fe, 0.056 %Si, $48.71, spread =  4
14 [21 10 17 ] 99.369 %Al, 0.239 %Fe, 0.344 %Si, $44.53, spread = 11
15 [37 43 38 ] 99.519 %Al, 0.169 %Fe, 0.143 %Si, $48.71, spread =  6
16 [11 12 15 ] 99.361 %Al, 0.068 %Fe, 0.309 %Si, $44.53, spread =  4
17 [ 8  1  2 ] 99.526 %Al, 0.042 %Fe, 0.230 %Si, $48.71, spread =  7
                                          Sum = $781.45, MxSprd = 11
```

7 My Best Solutions

These were found by using standard simulated annealing in C.

7.1 No Max Spread

```
 1 [13  4 26 ] 99.253 %Al, 0.210 %Fe, 0.373 %Si, $41.53, spread = 22
 2 [31 46 17 ] 99.500 %Al, 0.135 %Fe, 0.144 %Si, $48.71, spread = 29
 3 [49 14 29 ] 99.251 %Al, 0.207 %Fe, 0.314 %Si, $41.53, spread = 35
 4 [23 27 30 ] 99.505 %Al, 0.105 %Fe, 0.199 %Si, $48.71, spread =  7
 5 [20 50 10 ] 99.351 %Al, 0.220 %Fe, 0.327 %Si, $44.53, spread = 40
 6 [ 8 34 19 ] 99.353 %Al, 0.244 %Fe, 0.155 %Si, $44.53, spread = 26
 7 [ 1 48 24 ] 99.355 %Al, 0.069 %Fe, 0.342 %Si, $44.53, spread = 47
 8 [32  6  2 ] 99.500 %Al, 0.146 %Fe, 0.227 %Si, $48.71, spread = 30
 9 [40 36  7 ] 99.501 %Al, 0.169 %Fe, 0.121 %Si, $48.71, spread = 33
10 [28 25 43 ] 99.252 %Al, 0.218 %Fe, 0.369 %Si, $41.53, spread = 18
11 [21 45 16 ] 99.357 %Al, 0.199 %Fe, 0.232 %Si, $44.53, spread = 29
12 [ 9 47 39 ] 99.501 %Al, 0.095 %Fe, 0.228 %Si, $48.71, spread = 38
13 [37 35 11 ] 99.501 %Al, 0.067 %Fe, 0.277 %Si, $48.71, spread = 26
14 [22 15  3 ] 99.500 %Al, 0.089 %Fe, 0.165 %Si, $48.71, spread = 19
15 [18 42 44 ] 99.750 %Al, 0.044 %Fe, 0.136 %Si, $57.35, spread = 26
16 [51  5 38 ] 99.351 %Al, 0.192 %Fe, 0.349 %Si, $44.53, spread = 46
17 [41 33 12 ] 99.353 %Al, 0.099 %Fe, 0.305 %Si, $44.53, spread = 29
                                          Sum = $790.09, MxSprd = 47
```

7.2 Max Spread = 6

```
 1 [44,49,48,] 99.511 %Al, 0.169 %Fe, 0.145 %Si, $48.71, spread=5
 2 [18,19,21,] 99.512 %Al, 0.163 %Fe, 0.187 %Si, $48.71, spread=3
```

```
 3 [43,47,46,] 99.359 %Al, 0.172 %Fe, 0.315 %Si, $44.53, spread=4
 4 [9,11,12,] 99.535 %Al, 0.015 %Fe, 0.265 %Si, $48.71, spread=3
 5 [27,24,22,] 99.502 %Al, 0.068 %Fe, 0.194 %Si, $48.71, spread=5
 6 [36,39,34,] 99.502 %Al, 0.139 %Fe, 0.173 %Si, $48.71, spread=5
 7 [25,23,28,] 99.267 %Al, 0.185 %Fe, 0.332 %Si, $41.53, spread=5
 8 [38,37,42,] 99.650 %Al, 0.118 %Fe, 0.067 %Si, $52.44, spread=5
 9 [51,50,45,] 99.256 %Al, 0.198 %Fe, 0.351 %Si, $41.53, spread=6
 10 [2,7,5,] 99.505 %Al, 0.182 %Fe, 0.208 %Si, $48.71, spread=5
 11 [29,26,31,] 99.372 %Al, 0.094 %Fe, 0.350 %Si, $44.53, spread=5
 12 [16,14,20,] 99.298 %Al, 0.164 %Fe, 0.379 %Si, $41.53, spread=6
 13 [33,32,30,] 99.541 %Al, 0.070 %Fe, 0.160 %Si, $48.71, spread=3
 14 [6,8,10,] 99.352 %Al, 0.257 %Fe, 0.275 %Si, $44.53, spread=4
 15 [3,1,4,] 99.363 %Al, 0.151 %Fe, 0.284 %Si, $44.53, spread=3
 16 [13,15,17,] 99.276 %Al, 0.220 %Fe, 0.261 %Si, $41.53, spread=4
 17 [35,40,41,] 99.335 %Al, 0.141 %Fe, 0.317 %Si, $41.53, spread=6
Sum = $779.18, MxSprd = 6
```

7.3 Max Spread = 8

```
 1 [8,1,6,] 99.358 %Al, 0.130 %Fe, 0.315 %Si, $44.53, spread=7
 2 [24,27,21,] 99.506 %Al, 0.091 %Fe, 0.245 %Si, $48.71, spread=6
 3 [26,31,29,] 99.372 %Al, 0.094 %Fe, 0.350 %Si, $44.53, spread=5
 4 [32,40,34,] 99.353 %Al, 0.199 %Fe, 0.210 %Si, $44.53, spread=8
 5 [46,44,41,] 99.507 %Al, 0.108 %Fe, 0.191 %Si, $48.71, spread=5
 6 [22,15,18,] 99.514 %Al, 0.064 %Fe, 0.164 %Si, $48.71, spread=7
 7 [17,13,20,] 99.359 %Al, 0.191 %Fe, 0.305 %Si, $44.53, spread=7
 8 [38,33,35,] 99.501 %Al, 0.105 %Fe, 0.167 %Si, $48.71, spread=5
 9 [47,39,43,] 99.370 %Al, 0.153 %Fe, 0.341 %Si, $44.53, spread=8
 10 [7,2,5,] 99.505 %Al, 0.182 %Fe, 0.208 %Si, $48.71, spread=5
 11 [51,45,50,] 99.256 %Al, 0.198 %Fe, 0.351 %Si, $41.53, spread=6
 12 [12,16,19,] 99.362 %Al, 0.204 %Fe, 0.275 %Si, $44.53, spread=7
 13 [11,9,14,] 99.381 %Al, 0.080 %Fe, 0.297 %Si, $44.53, spread=5
 14 [36,30,37,] 99.654 %Al, 0.098 %Fe, 0.129 %Si, $52.44, spread=7
 15 [10,3,4,] 99.357 %Al, 0.278 %Fe, 0.244 %Si, $44.53, spread=7
 16 [49,48,42,] 99.513 %Al, 0.147 %Fe, 0.139 %Si, $48.71, spread=7
 17 [28,25,23,] 99.267 %Al, 0.185 %Fe, 0.332 %Si, $41.53, spread=5
Sum = $784.00, MxSprd = 8
```

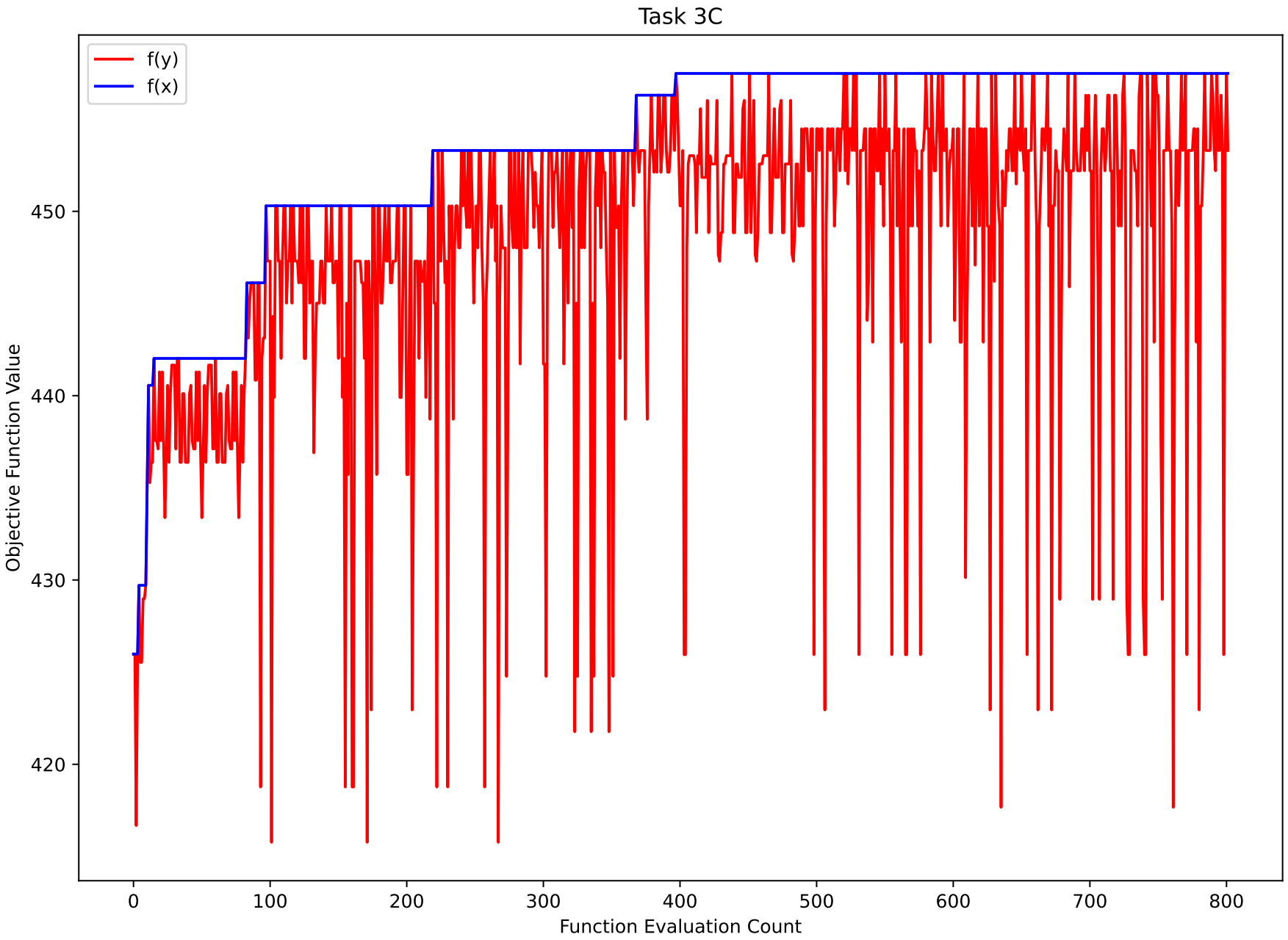
7.4 Max Spread = 11

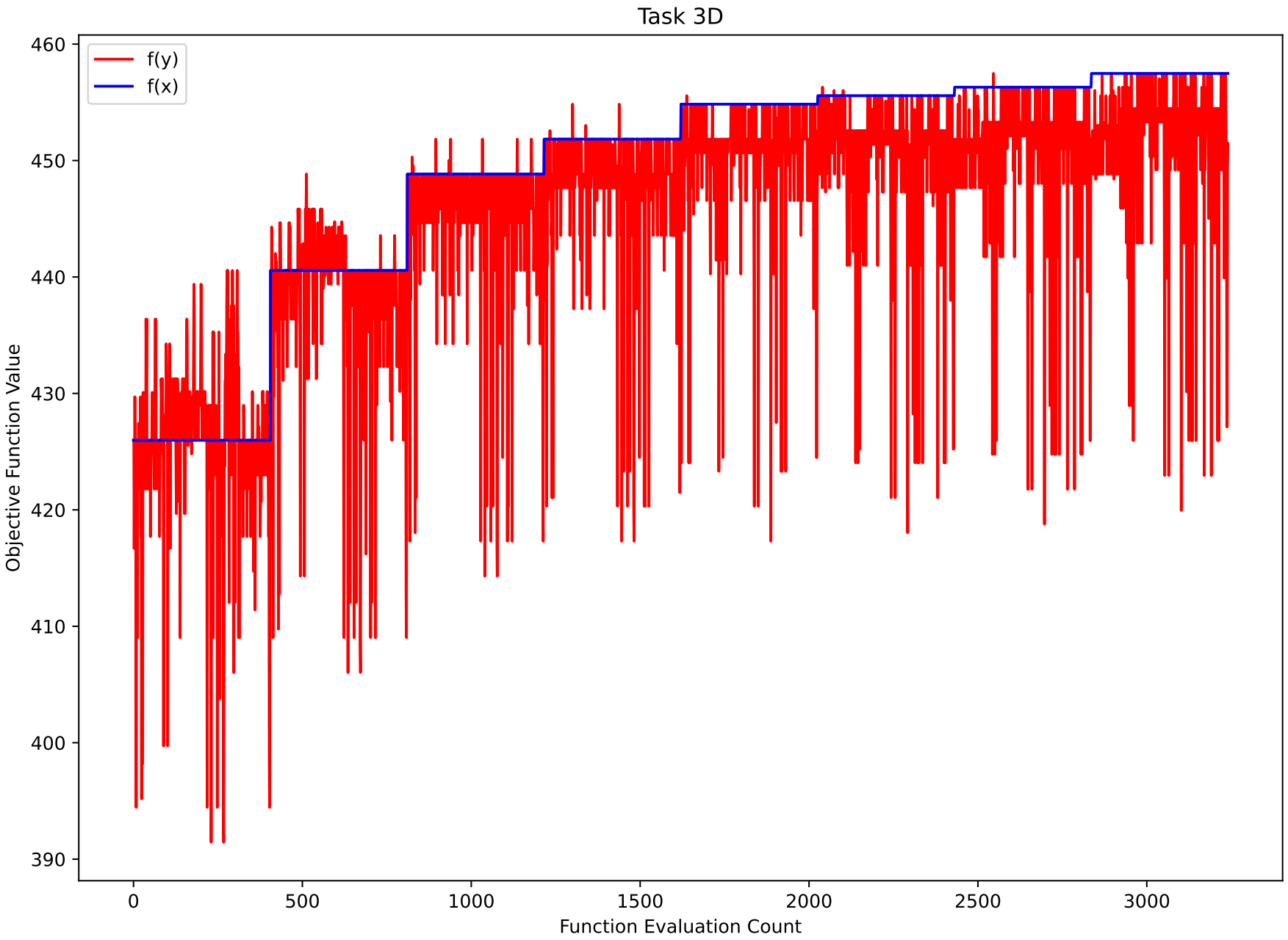
```
 1 [24,19,26,] 99.355 %Al, 0.140 %Fe, 0.305 %Si, $44.53, spread=7
 2 [27,33,37,] 99.500 %Al, 0.148 %Fe, 0.086 %Si, $48.71, spread=10
 3 [38,28,34,] 99.262 %Al, 0.236 %Fe, 0.270 %Si, $41.53, spread=10
 4 [48,50,41,] 99.351 %Al, 0.151 %Fe, 0.329 %Si, $44.53, spread=9
 5 [49,43,51,] 99.294 %Al, 0.189 %Fe, 0.367 %Si, $41.53, spread=8
 6 [44,47,39,] 99.500 %Al, 0.124 %Fe, 0.270 %Si, $48.71, spread=8
```

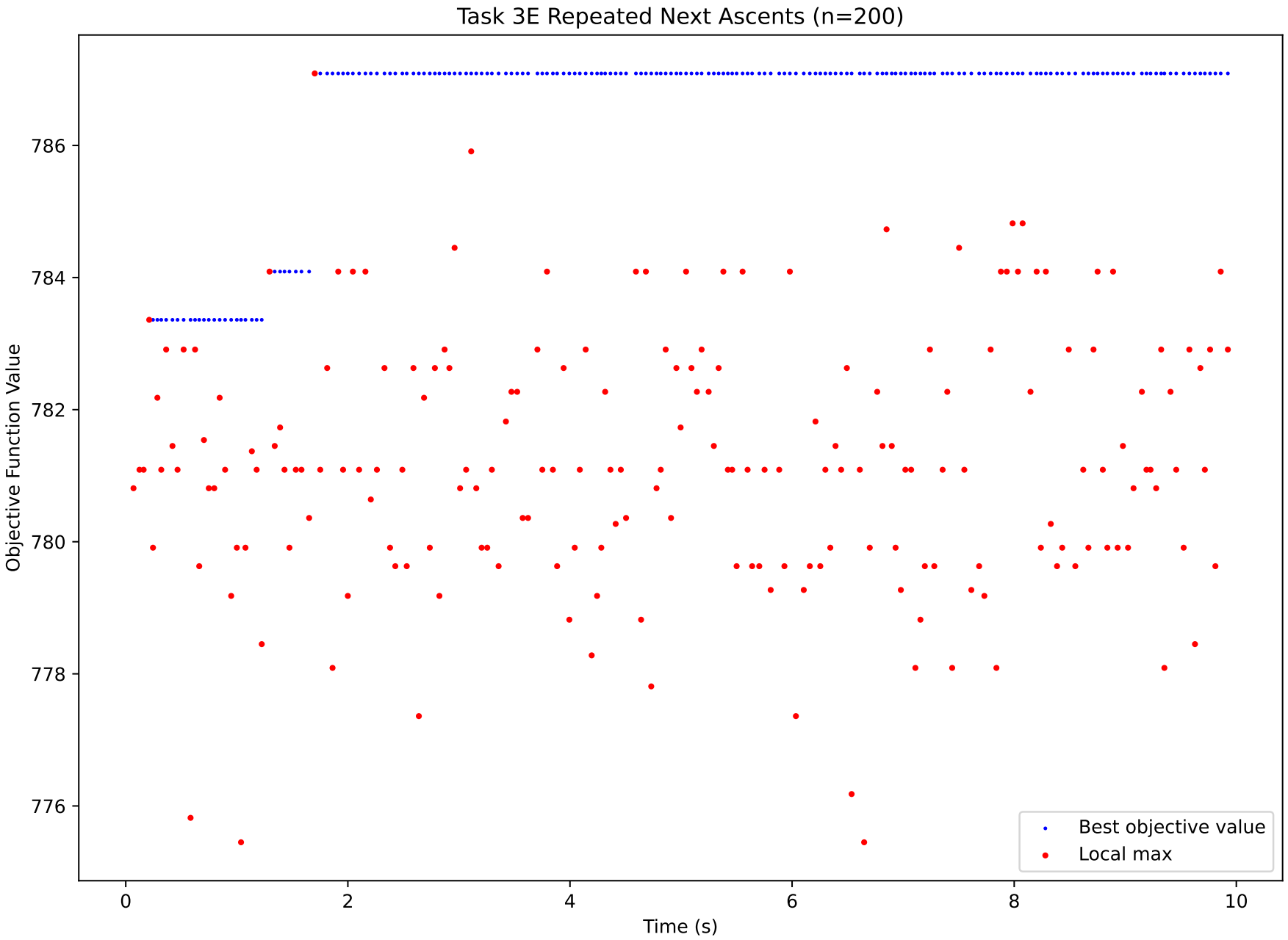
```
 7 [42,36,45,] 99.504 %Al, 0.145 %Fe, 0.069 %Si, $48.71, spread=9
 8 [35,46,40,] 99.504 %Al, 0.110 %Fe, 0.193 %Si, $48.71, spread=11
 9 [4,3,1,] 99.363 %Al, 0.151 %Fe, 0.284 %Si, $44.53, spread=3
 10 [10,6,8,] 99.352 %Al, 0.257 %Fe, 0.275 %Si, $44.53, spread=4
 11 [32,31,21,] 99.501 %Al, 0.089 %Fe, 0.201 %Si, $48.71, spread=11
 12 [14,15,12,] 99.251 %Al, 0.139 %Fe, 0.370 %Si, $41.53, spread=3
 13 [9,11,17,] 99.512 %Al, 0.072 %Fe, 0.221 %Si, $48.71, spread=8
 14 [30,20,23,] 99.503 %Al, 0.072 %Fe, 0.255 %Si, $48.71, spread=10
 15 [29,25,18,] 99.505 %Al, 0.134 %Fe, 0.271 %Si, $48.71, spread=11
 16 [16,13,22,] 99.374 %Al, 0.167 %Fe, 0.288 %Si, $44.53, spread=9
 17 [7,2,5,] 99.505 %Al, 0.182 %Fe, 0.208 %Si, $48.71, spread=5
Sum = $785.63, MxSprd = 11
```

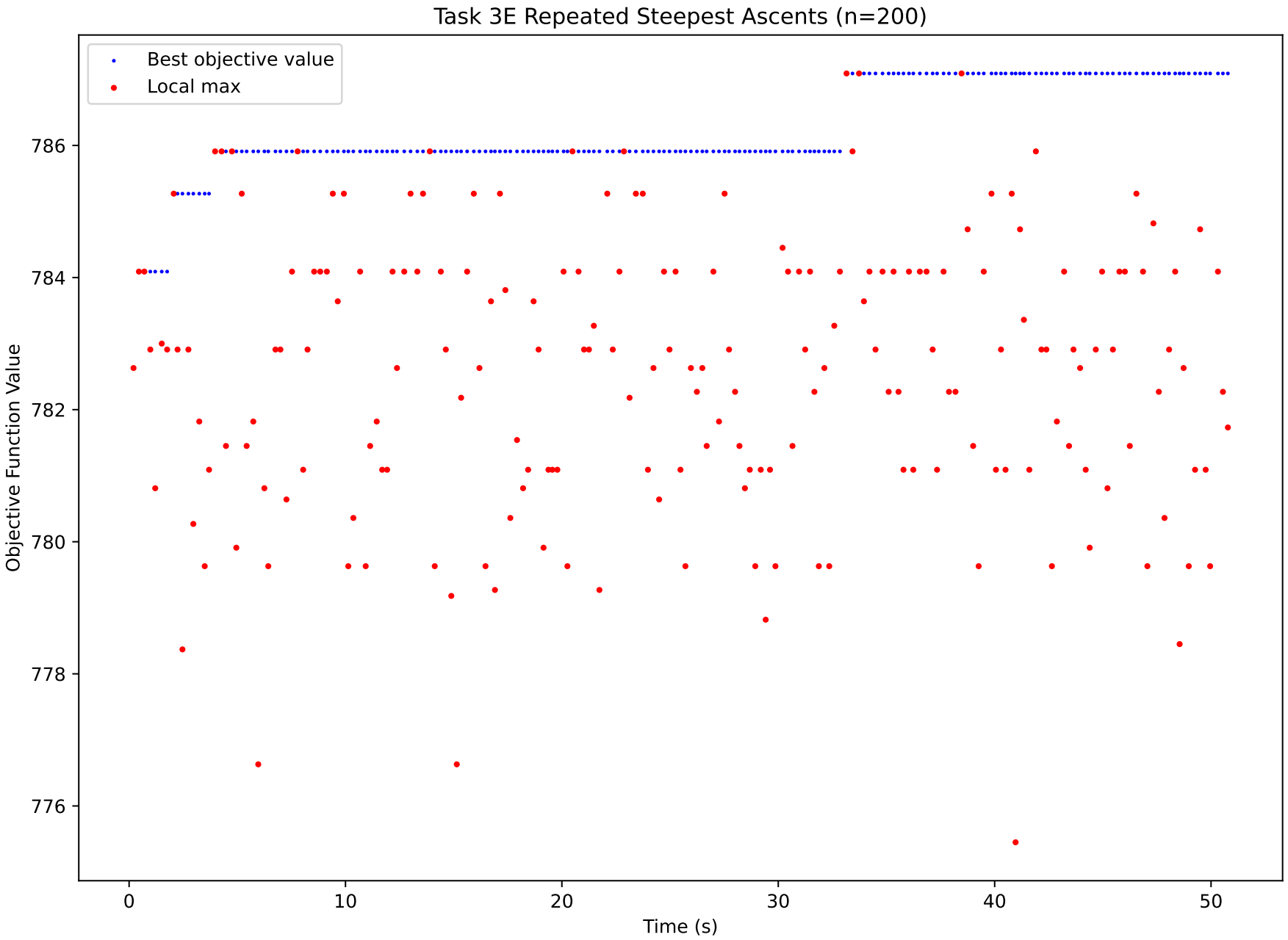
8 Appendix A

See overleaf


Task 3C
f(y)
f(x)
Objective Function Value
450
440
430
420
0
100
200
300
400
500
600
700
800
Function Evaluation Count


Task 3D
f(y)
f(x)
460
450
440
430
420
410
400
390
Objective Function Value
0
500
1000
1500
2000
2500
3000
Function Evaluation Count


Task 3E Repeated Next Ascents (n=200)
Objective Function Value
786
784
782
780
778
776
0
2
4
6
8
10
Time (s)
Best objective value
Local max


Task 3E Repeated Steepest Ascents (n=200)
Best objective value
Local max
Objective Function Value
786
784
782
780
778
776
0
10
20
30
40
50
Time (s)