

# ON TUNING THE DESIGN OF AN EVOLUTIONARY ALGORITHM FOR MACHINING OPTIMIZATION PROBLEMS

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**Keywords:** Evolutionary algorithms, Experimental Algorithmics, Optimization of machining parameters.

**Abstract:** In this paper, a novel method for tuning the design of an evolutionary algorithm (EA) is presented. The ADT method was built from a practical point of view, for including an EA into a framework for optimizing machining processes under uncertainties. The optimization problem studied, the algorithm, and the computer experiments made using the ADT method are presented with many details, in order to enable the comparison of this method with actual methods available to tune the desing of evolutionary algorithms.

## 1 INTRODUCTION

A mathematical framework for optimizing machining processes with uncertainties, called the Robust Optimizer, is currently being developed at the National Institute of Standards and Technology (NIST), as a part of the Smart Machining Systems Research Program (Deshayes et al., 2005b). The goal of this framework is to provide a process optimization capability for machine-tools, integrated with the CAD/CAM systems and the machine-tool controllers. Optimization of machining processes is a difficult task which has been studied since the beginning of the last century. As an example, the selection of optimal cutting parameters involves the development of machining models, and optimization algorithms able to handle those models. Taylor built the first experimental models in a seminal study (Taylor, 1907); after him many different models and optimization algorithms were developed. The class of optimization problems encountered can be linear, convex non-linear, or non-convex as shown by Deshayes *et al.* (Deshayes et al., 2005a). For example in high-speed machining processes, the constraint for chatter stability is defined by a non-convex function. Additionally, as shown by Kurdi *et al.* (Kurdi et al., 2005), uncertainties on model parameters may strongly influence the limit

contours of the constraint. As a consequence, the framework under development must contain several algorithms for optimization under uncertainties such as robust linear programming, stochastic programming, depending on the class of optimization problems. Vigouroux *et al.* (Vigouroux et al., 2007) presented a novel optimization algorithm to fit into the framework, for non-convex problems, by coupling an evolutionary algorithm with interval analysis. EA are algorithms from the Artificial Intelligence domain. The main mechanism of EA is an iterative sampling of candidate solutions to find the optimal one, for more information see the book of Yao (Yao, 1999). The latest applications of EA include Pattern recognition (Raymer et al., 2000), multi-disciplinary optimization for car design (Rudenko et al., 2002). EA have already been applied in machining by Wang *et al.* (Wang et al., 2002) to a non-convex optimization problem without uncertainties. EA are algorithms that require tuning of their parameters to obtain optimal results regarding execution time, convergence, and accuracy. Moreover the parameters must be robust for a range of similar problems.

The design of evolutionary algorithms, that is the choice of an EA architecture and algorithm parameters, robust to problem parameter changes, or adapted to several problems is not straightforward. There-

fore, evolutionary algorithms have found applications in specific optimization problems where the tuning of the algorithm can be performed by the user. Several methods to help this design were introduced recently by Francois and Lavergne (Francois and Lavergne, 2001), Nannen and Eiben (Nannen and Eiben, 2006). Nannen and Eiben were interested to design an evolutionary system to study evolutionary economics. For that complex system, EA are not just an optimization algorithm but also a model for simulating evolution. Therefore the EA used by Nannen and Eiben contain much more parameters than the EA studied here: over ten. Nannen and Eiben don't have an alternate method at hand to find the optimum solution, mainly because the EA studied does not perform optimization. To optimize the parameters of the EA, they built the CRE method, by considering a trade-off between a performance index, the average response of the EA, and the average algorithm complexity, for 150 samples of the algorithm parameters. To take in account similar problems, they let vary three problem parameters and do 18 experiments. For each of them, an iterative routine determines automatically the optimal values of the algorithm parameters, based on the trade-off. Then the optimal values of the parameters are found as the average over all experiments.

The relevance of such methods is important to integrate EA in the Robust Optimizer. Machining problems have many parameters subject to changes. In this paper, an alternative method to the CRE method, the algorithm design tuning (ADT) method, is presented for helping the design of an EA for machining optimization problems. It makes use of statistical engineering tools not only to optimize the algorithm parameters, but to modify the EA design in order to avoid non-convergence. In the background of the study are presented the example turning problem used for building the Robust Optimizer, along with the EA able to solve it, and some notions about experimenting with algorithms. Then the novel ADT method is introduced along with experimental results and a comparison with the CRE method.

## 2 BACKGROUND

### 2.1 Example Turning Problem for the Robust Optimizer

An optimization problem consists of optimizing an objective function while satisfying several constraints:

$$\text{Minimize } \mathbf{f}(\mathbf{x})$$

$$\text{subject to } g_j(\mathbf{x}) \leq 0 \quad j = 1, 2, \dots, p$$

where  $\mathbf{f}$  is the objective function,  $g_j$  a constraint function, and  $\mathbf{x}$  is a vector of real variables, called a solution of the problem. The vectors  $\mathbf{x}^l$  and  $\mathbf{x}^u$  define the lower and upper bounds for the variables, and are specified in some of the constraint equations  $g_j$ . These bounds define the search space.

The turning problem is a two-variable optimization problem, with a set of specific values for the problem parameters. The variables and parameters used in the problem are presented below:

- $f$ - Feed,  $mm/rev$
- $Vc$ - Cutting speed,  $m/s$
- $a_p$ - Depth of cut,  $mm$
- $f_{min}$ - Minimum Feed,  $mm/rev$
- $f_{max}$ - Maximum Feed,  $mm/rev$
- $Vc_{min}$ - Minimum Cutting speed,  $m/s$
- $Vc_{max}$ - Maximum Cutting speed,  $m/s$
- $Pu$ - Spindle power,  $W$
- $Cu$ - Spindle torque,  $Nm$
- $Ra_{spe}$ - Workpiece desired surface roughness,  $\mu m$
- $Ra$ - Workpiece surface roughness,  $\mu m$
- $K_1, \delta r_{epsilon}$ - Constants in surface roughness equation
- $r_{epsilon}$ - Tool nose radius,  $mm$
- $F_c$ - Cutting force,  $N$
- $K_c$ - Constant in cutting force equation
- $tc$ - Exponent in cutting force equation
- $T$ - Tool life,  $s$
- $T_r, f_r, a_{pr}, Vc_r$ - Constants in tool life equation
- $n, m, l$ - Exponents in tool life equation
- $t_{cut}$ - Cutting time,  $s$
- $N_{parts}$ - Desired number of parts to cut per tool
- $A$ - Workpiece equivalent cutting surface,  $mm^2$
- $D_{av}$ - Workpiece average diameter,  $mm$
- $L_c$ - Workpiece equivalent length of cut,  $mm$

The goal is to find the optimal machining parameters, feed and speed, which maximize the material removal rate (MRR) of one turning pass, considering several process constraints. The two variables to be optimized are the feed  $f$  and the cutting speed  $Vc$ . The mathematical functions of the problem are detailed below:

The objective function is defined as the opposite of MRR in order to solve a minimization problem<sup>1</sup>:

$$\mathbf{f}(f, Vc) = -ap \times f \times Vc \quad (1)$$

The constraint function of minimum feed, C1:

$$g_1(f, Vc) = f_{min} - f \quad (2)$$

The constraint function of maximum feed, C2:

$$g_2(f, Vc) = f - f_{max} \quad (3)$$

<sup>1</sup>To maximize an objective function is the same as to minimize its negative opposite.

The constraint function of minimum cutting speed, C3:

$$g_3(f, Vc) = Vc_{min} - Vc \quad (4)$$

The constraint function of maximum cutting speed, C4:

$$g_4(f, Vc) = Vc - Vc_{max} \quad (5)$$

The constraint function of surface roughness, C5:

$$g_5(f, Vc) = Ra(f) - Ra_{spe} \quad (6)$$

The constraint function of tool life, C6:

$$g_6(f, Vc) = T(f, Vc) - t_{cut}(f, Vc) \quad (7)$$

The constraint function of Spidle power life, C7:

$$g_7(f, Vc) = Pu - Fc(f, Vc) \times Vc \quad (8)$$

Several functions have variables defined by the equations presented below. The tool life equation is obtained from Taylor's work (Taylor, 1907):

$$T(f, Vc) = T_r \frac{a_p^{-l} f^m Vc^n}{a_{pr} f_r \cdot V_{cr}} \quad (9)$$

The cutting time,  $t_{cut}$ , is obtained from the following equation:

$$t_{cut}(f, Vc) = N_{parts} \frac{A}{f \times Vc \times 1000}, \quad (10)$$

where  $A$  is obtained from the following equation:

$$A = \pi \times D_{av} \times L_c. \quad (11)$$

The surface roughness equation is obtained from the study by Deshayes *et al.* (Deshayes *et al.*, 2005a):

$$Ra(f) = K_1 f \frac{\delta r_{epsilon}}{r_{epsilon}}. \quad (12)$$

The cutting force equation is obtained from an experimental study by Ivester *et al.* (Ivester *et al.*, 2006):

$$Fc(f) = Kc \times f^{1+tc} \times ap. \quad (13)$$

The original problem has parameter values given in Table (1). For this original problem, the limit contours of the constraint functions are represented in Figure (1). Ten parameters of this problem can be modified and are specified in Table (1). The parameter ranges of this table are determined by knowledge of machining and judgement.

## 2.2 Evolutionary Algorithms

In Darwin's evolution theory (Darwin, 1859), a population of individuals evolves over several generations. The individuals with the best fitness, determined by their genes, are selected to breed; their children form the next population. Since offspring of individuals

Table 1: Problem parameter ranges.

Parameter name	Original value	Minimum value	Maximum value	Factor name
$Vc_{min}$	1.83	1.33	2.5	X1
$Vc_{max}$	7.5	6.5	10	X2
$f_{min}$	0.2	0.1	0.3	X3
$f_{max}$	0.6	0.5	0.8	X4
$a_p$	2	1	4	X5
$Kc$	2000	1800	2500	X6
$Pu$	15000	15000	20000	X7
$D_{av}$	72	60	80	X8
$Lc$	550	350	650	X9
$Ra_{spe}$	4.5	3	5	X10

with best fitness should be better suited to survive within their environment, the species improves. Thus, over time and several generations, evolution leads to the adaptation of the population to the environment.

This theory is used by the implemented Evolutionary Algorithm (EA). The optimization variables play the role of the individuals' genes. The EA is presented as a class written in the Python language<sup>2</sup>. The constructor function of this class is presented below:

```
class EA:
    def __init__(self):
        self.gene_size=2
        x1bounds=[0.2,0.6]
        x2bounds=[1.83,7.5]
        self.bounds = [x1bounds,x2bounds]
        self.N = 50
        self.alpha=0.4
        self.z=20
```

The constructor sets the number of genes per individual (here two), the bounds of variables, the population size  $N$ , the breeding parameter  $\alpha$ , and the number of generations  $z$ . The `run_algorithm` function contains the algorithm steps and is presented here:

```
def run_algorithm():
    population = population_initialize()
    for i in range(self.z):
        parent_population =
            tournament_selection(population)
        children_population =
            breeding(parent_population)
        population = children_population
    return population[1]
```

<sup>2</sup>Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose. Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

The EA has the following steps:

- **Construction of the initial population.** The `population_initialize` function, presented below, outputs a first population of  $N$  individuals spread uniformly over the search space, by use of a random function giving a number between zero and one. The fitness function,  $h$ , of one individual is computed with the static penalty method, and is given in Equation (14). Michalewicz *et al.* (Michalewicz *et al.*, 1996) reviewed several methods that enable EA to handle optimization problems with constraints, and explain this method with more details.

```
def population_initialize():
    population = []
    for i in range(self.pop_size):
        population.append([])
        for j in range(self.gene_size):
            population[i].append(self.bounds[j][0]+
                (self.bounds[j][1]
                - self.bounds[j][0])*random())
            population[i].append(fitness(population[i]))
    return population
def fitness(genes):
    result=h(genes)
    return result
```

$$h(\mathbf{x}) = -sf(\mathbf{x}) + W \times \sum_{j=1}^n sg_j(x) \quad (14)$$

with

$$sf(x) = \frac{\mathbf{f}(\mathbf{x})}{\mathbf{f}(\mathbf{x}^u)} \quad (15)$$

and

$$sg_j(\mathbf{x}) = \frac{g_j(\mathbf{x})}{g_j(\mathbf{x}^u)} \quad \text{if } g_j(\mathbf{x}) \leq 0, \quad 0 \quad \text{else} \quad (16)$$

$W$  is the static penalty parameter. This parameter controls the degradation of the fitness function when one or more constraints are violated. In this article, the value of  $W$  is ten.

- **Selection.** The `tournament_selection` function, presented below, outputs a parent population of  $N/2$  individuals. These individuals are selected by  $N/2$  tournaments of size 2: for each tournament two individuals are randomly picked in the population and their fitness functions are compared. The individual with the higher fitness value wins and is added to the parent population. The loser re-enters the population and can eventually participate in another tournament.

```
def tournament_selection(population):
    pool_size=self.N/2
    parent_population = []
    for i in range(pool_size):
        parent_population.append([])
        match = Structure()
        match.pool = sample(population,2)
```

```
match.knight1=match.pool[0]
match.knight2=match.pool[1]
if match.knight1[2] <match.knight2[2]:
    match.winner = match.knight1
elif match.knight1[2] ==match.knight2[2]:
    match.winner = match.knight1
else:
    match.winner = match.knight2
parent_population[i] = match.winner
return parent_population
```

- **Breeding.** The breeding function, presented below, outputs a new children population. Two individuals are randomly picked from the parent population. Two new individuals are created in a box. The position of this box within the search space is defined by the two parents' genes. The dimensions of the box are defined by both a breeding parameter called  $\alpha$  and the two parents' genes. This process of creating individuals is called blend crossover and was introduced by Eschelman and Schaffer (Eschelman and Schaffer, 1993). It is repeated  $N/2$  times in order to produce a children population having  $N$  individuals.

```
def breeding(parent_population):
    children_population = []
    for i in range(self.pool_size):
        parents = sample(parent_population,2)
        parent1 = parents[0]
        parent2 = parents[1]
        children1 = []
        children2 = []
        for j in range(self.gene_size):
            a= -self.alpha +(1+2*self.alpha)*random()
            children1.append(a*parent1[j] +
                (1-a)*parent2[j])
            a= -self.alpha +(1+2*self.alpha)*random()
            children2.append(a*parent1[j] +
                (1-a)*parent2[j])
        children1.append(fitness(children1))
        children2.append(fitness(children2))
        children_population.append(children1)
        children_population.append(children2)
    return children_population
```

At the next generation, this new population will face again the selection step and the loop will continue until the number of generations  $z$ , is attained. When the algorithm is stopped, the first individual in the population, with genes  $(x_{11}, x_{21})$ , is picked. The objective function  $MRR_z$  is computed for this individual in Equation (17) and is the result output by the algorithm.

$$MRR_z = a_p \times x_{11} \times x_{21} \quad (17)$$

For the original problem, the populations at several generations are plotted in Figure (1). The initial population is represented by stars, the population at generation 2 is represented by circles, and the population at generation 5 is represented by diamonds. The

evolution of the center of gravity of the population over several generations defines a track represented by crosses and dashed lines. This algorithm has three influential parameters: the breeding parameter  $\alpha$ , the population size  $N$ , and the number of generations,  $z$ . Tuning of these parameters is required to enhance the performance of the algorithm.

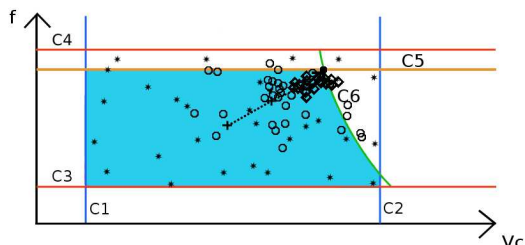


Figure 1: Populations at several generations during one run of the EA.

### 2.3 Experimental Algorithmics

Experimental Algorithmics refer to the study of algorithms through a combination of experiments and classical analysis and design techniques.

Since EA are randomized algorithms, their results are unequal run after run, even though all parameters may remain the same. Therefore, it is necessary to run the EA several times to report an average result. Thus, the computational expense associated with the tuning of the algorithm may become important. Statistical techniques such as design of experiments and response surface methodology avoid this computational expense and are presented in (NIST/SEMATECH, 2006) and (Box et al., 1978).

A computer experiment refers here to a run of the EA with a set of algorithm parameters and a set of problem parameters. With the design of experiments, the problem parameters are renamed factors, see Table (1); a design stands for a set of experiments, with each experiment having a specific combination of factor levels. When considering only two levels of variation for each problem parameter, the low settings and the high settings presented in Table (1), there are 1024 possible combinations. A full factorial design is a set with all possible factor levels combinations, here  $2^{10} = 1024$ . A more efficient design is an orthogonal fractional factorial design (NIST/SEMATECH, 2006), with only 128 runs, ten percent of the full factorial design.

According to the response surface terminology (Box et al., 1978), the measures made during the experiments are referred to as response variables.

For the design of the EA, three response variables are considered:

- $y_1$  is an index defining the accuracy of the EA:

$$y_1 = \frac{MRR_z}{MRR^*} \quad (18)$$

where  $MRR^*$  is the optimal material removal rate of the problem, corresponding to the optimal solution.  $MRR^*$  can be obtained graphically or by another optimization algorithm able to find it. Since  $MRR$  is an increasing function, The expected range of  $y_1$  is between 0 and 1. If the value of  $y_1$  is greater, the result  $MRR_z$  output by the algorithm is unacceptable and it means that the algorithm did not converge.

- $y_2$  is the count of non-convergence cases after several runs of the algorithm. Those non-convergence cases are detected by values of  $y_1$  higher than 1.
- $y_3$  is a time measure in seconds, related to the execution time of the EA.

The set-up of the computer experiments is given: The EA is implemented with Matlab software on a personal computer. The computer processor is an Intel Pentium 4 with a frequency of 3.80 GHz, running with a memory of size 2 GB. The measure of  $y_3$  is made using Matlab's `cputime` function.

The random function used to generate the necessary random behaviors in the algorithm is Matlab's **random** function with the **Seed** method. It generates a pseudo-random number between 0 and 1. After a certain number of calls,  $2^{31} - 1$ , the function repeats itself. This function takes as the argument a number called the seed. The seed defines the internal state of the function and, with the same seed, the random function generates the same sequence of random numbers. Therefore, all the seeds used in the experiments were recorded and stored, giving the possibility to reproduce exactly the same experimental results. Each computer experiment was replicated ten times with different seeds.

Once the computer experiments have been made, the Exploratory Data Analysis (EDA) techniques (Tukey, 1977) can be used to explore the results. These techniques allow to ferret out interesting attributes of the result data. The Dataplot statistical engineering software was used in this study to perform EDA. Sensitivity analysis is a technique that allows to order the problem parameters according to the effect of their variation on the response. The order of the parameter can be deduced from a plot called the main effect plot. An example plot is shown in Figure (3).

### 3 THE ADT METHOD

#### 3.1 Step 1: Preliminary Exploratory Data Analysis

The first step of the methodology is to perform an exploratory analysis. The goal is to see how much the algorithm performances vary, and to establish if the algorithm needs any modifications of its architecture. This analysis requires performing computer experiments with a set of algorithm parameters  $(\alpha, N, z)$ , according to the orthogonal fractional factorial design introduced previously. This step requires a special plot of the response  $y_1$ : the responses of all experiments are ordered and plotted, as shown in Figure (2). The experiments where the algorithm does not converge are detected by values of  $y_1$  exceeding one. The reason for non-convergence can be discovered by plotting the limit contours of the constraints for the case with non convergence, similarly to Figure (1) presented previously. Then the algorithm architecture may be modified, in order to be adapted to the non-convergence cases.

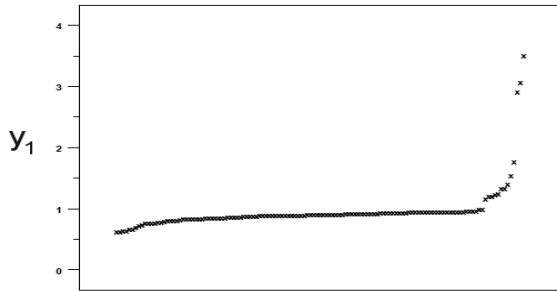


Figure 2: Ordered data plot of response  $y_1$  for the exploratory analysis of the set  $(\alpha = 0.4, N = 40, z = 20)$ .

#### 3.2 Step 2: Sensitivity Analysis

This step is optional. This step may only be required if the problem has more than two optimization variables, where it may be impossible to plot the limit contours of the constraints for the case with non-convergence. In that case the reason for non-convergence cannot be easily discovered. The sensitivity analysis allows to determine the most important problem parameters affecting the response  $y_1$ . The main effect plot in Figure (3) shows the variation of the response  $y_1$  depending on the variation of the problem parameters.

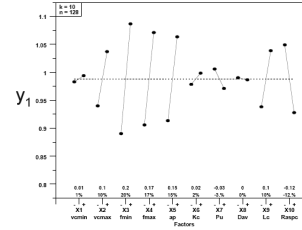


Figure 3: Main effect plot of response  $y_1$  for the sensitivity analysis of the set  $(\alpha = 0.4, N = 40, z = 20)$ .

#### 3.3 Step 3: Optimization

In this step the algorithm parameters are optimized  $(\alpha, N, z)$ .  $\alpha, N, z$  can be chosen respectively in the range  $[20, 200], [0.1, 0.9]$  and  $[10, 50]$ . Given a set  $(\alpha, N, z)$ , a sensitivity analysis is performed as previously discussed, but the results of each computer experiment are now three responses,  $y_1, y_2$ , and  $y_3$ . The goal is to optimize the average values of the responses: maximize  $\bar{y}_1$ , minimize  $\bar{y}_2$ , minimize  $\bar{y}_3$ .

First, only the first objective  $\bar{y}_1$  is considered. Since the computational expense of the sensitivity analysis necessary to compute  $\bar{y}_1$  is high, only a small number of sets  $(\alpha, N, z)$  can be investigated. The response surface methodology is applied to find the best set  $(\alpha, N, z)$ . Starting with an initial guess  $(\alpha_0, N_0, z_0)$ , several other sets in the neighborhood are tested, whose values are defined by an orthogonal full factorial design. This design has 3 factors and 11 experiments. The choice of the parameter ranges, centered around the set  $(\alpha_0, N_0, z_0)$ , is left to the user.

The result  $\bar{y}_1$  of each tested set  $(\alpha, N, z)$  can be visualized as a cube, as shown in Figure (4). From the analysis of the cube, a new center set  $(\alpha_1, N_1, z_1)$  is chosen, to explore the space in the region where the optimum value of  $\bar{y}_1, \bar{y}_1^*$ , could be located. Again, computer experiments are performed with the same design but with different parameter ranges, in order to acquire the new cube with center  $(\alpha_1, N_1, z_1)$ . This iterative process can be repeated as long as needed in order to find  $\bar{y}_1^*$ . The cubes for the objectives  $\bar{y}_2$  and  $\bar{y}_3$  can be acquired at the same time, although the optimum values for these objectives are not found. This method enables one to explore the spaces  $\bar{y}_2$  and  $\bar{y}_3$  as functions of variables  $(\alpha, N, z)$ . After the three objective spaces have been explored, the user is able to pick a set  $(\alpha, N, z)$ , that has good values  $\bar{y}_1, \bar{y}_2$ , and  $\bar{y}_3$ , although not optimal. This set represents a compromise between best accuracy, best convergence, and best execution time.

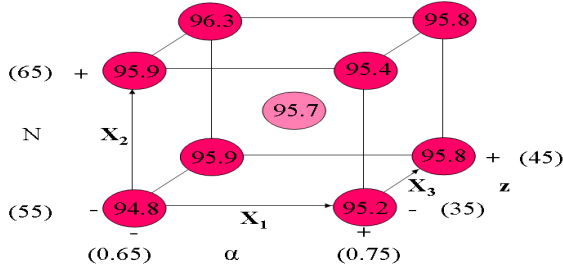


Figure 4: The responses  $y_1$  multiplied by 100 for the cube with center  $(\alpha_0 = 0.7, N_0 = 60, z_0 = 40)$ .

### 3.4 Validation of the Optimized Algorithm

The algorithm is optimized with a sample of problem parameter combinations and a sample of seeds. This sample can be termed a training data set, and an analogy can be drawn with the training of neural networks. Now the performance results of the algorithm must be verified with a new sample of data: the validation data set.

In order to compare the average performance results, a validation data set of the same size as the training data set must be chosen. A different sampling of the problem parameter combinations is made. A Latin hypercube sampling is used with the same size as the orthogonal design presented in Section (2.3): 128 values for each of the ten factors. A new sample of 100 different seeds is also picked and stored. The sensitivity analysis can be replicated ten times with the new data and the results compared.

### 3.5 Results

The preliminary exploratory analysis was performed on the set  $(\alpha = 0.4, N = 40, z = 20)$ . The ordered data plot of response  $y_1$ , shown in Figure (2), revealed non-convergence cases, detected on the right of the plot by values exceeding one. The limit contours of the constraints were plotted for some of the non-convergence cases, and it was discovered that the initialization step was not adapted. To avoid this problem, it was decided to change the initialization so that the first population is spread in the lower left quarter of the search space. The sensitivity analysis, shown in Figure (3), was performed, but all the information provided by this step was already known from the plots of the first step.

In the third step, optimization was performed with an initial guess  $(\alpha_0 = 0.7, N_0 = 60, z_0 = 40)$ . After three iterations, it was found that  $y_1^*$  should have a value around 0.97, and a good confidence was ac-

quired about the knowledge of the three objective spaces. The set of algorithm parameters selected is  $(\alpha = 0.6, N = 60, z = 40)$ . The results of a sensitivity analysis of this set, replicated ten times, is shown in Table (2). During the validation step, a compar-

Table 2: Optimization step: results for the set  $(\alpha = 0.6, N = 60, z = 40)$  with the training data set.

	Response variable $y_1$	Response variable $y_2$	Response variable $y_3$ (s)
average	0.950	1	1.130
standard deviation	0.002	1.05	0.003

son was made between the results obtained with the training data set and the results obtained with the validation data set. The later results presented in Table (3) are slightly better. Therefore, the training method used to tune the algorithm seems to be sound.

Table 3: Validation step: results for the set  $(\alpha = 0.6, N = 60, z = 40)$  with the validation data set.

	Response variable $y_1$	Response variable $y_2$	Response variable $y_3$ (s)
average	0.966	0	1.123
standard deviation	0.001	0.00	0.002

### 3.6 Comparison with the Cre Method

The ADT method was developed for the turning problem of the Robust Optimizer. From this point of view the EA has few parameters, three, and quite a lot of problem parameters, ten. On the contrary, the CRE method considers many EA parameters and few problem parameters. The reason why the CRE method does not consider many problem parameters may be a reason of time consumed to perform the experiments, as indicated in the paper by Nannen and Eiben (Nannen and Eiben, 2006). The ADT method required also a lot of time to perform the experiments. For both methods, increasing the number of algorithm parameters and problem parameters considered is a problem, so the complexity of the CRE and ADT methods should be determined and compared.

The CRE method relies on information theory to determine the importance of the algorithm parameters. This point is not adressed by the ADT method. During the study, it was decided to remove the mutation parameter from the algorithm by studying videos showing the populations evolve over the search space, during several iterations. This kind of decision was made possible because of the low dimension of the optimization problem studied: only two variables.

The ADT method enables to optimize very practical responses of EA: the execution time, the number of non-convergence cases, the accuracy. For the last objective, accuracy, one needs to know the optimal solution for each optimization problem. This is possible graphically only for low dimension optimization problems. For optimization problems of higher dimension, an alternative optimization algorithm must be used.

Since this method was developed concurrently with the CRE method, an experimental comparison of the two methods was not possible. However all details are given in this paper to perform such a study.

## 4 CONCLUSION

The novel ADT method presented here enables tuning the design of an EA for optimizing a turning process with uncertainties. The ADT method also enables the algorithm designer to manage several performance objectives. The method is an alternative method to the CRE method, and focuses on the practical objectives of accuracy, non-convergence and execution time. In the future, the two methods need to be compared. For the Robust Optimizer, an optimization problem involving a milling process needs to be considered, to see if the ADT method enables to design an EA for optimizing different kinds of machining processes, or not.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and assistance of Robert Ivester, David Gilsinn, Florian Potra, Shawn Moylan, and Robert Polvani, from the National Institute of Standards and Technology.

## REFERENCES

- Box, G. E. P., Hunter, W. G., and Hunter, J. S. (1978). *Statistics for Experimenters*. John Wiley.
- Darwin, C. (1859). *On the origin of species by means of natural selection*. John Murray.
- Deshayes, L., Welsch, L., Donmez, A., and Ivester, R. W. (2005a). Robust optimization for smart machining systems: an enabler for agile manufacturing. In *Proceedings of IMECE2005: 2005 ASME International Mechanical Engineering Congress & Exposition*.
- Deshayes, L., Welsch, L., Donmez, A., Ivester, R. W., Gilsinn, D., Rohrer, R., Whitenton, E., and Potra, F. (April 3-5, 2005b). Smart machining systems: Issues and research trends. In *Proceedings of the 12th CIRP Life Cycle Engineering Seminar*.
- Eschelmann, L. and Schaffer, J. D. (1993). *Real-coded genetic algorithms and interval-schemata*. Morgan Kaufmann.
- Francois, O. and Lavergne, C. (2001). Design of evolutionary algorithms—a statistical perspective. *IEEE Transactions on Evolutionary Computation*, 5(2):129–148.
- Ivester, R. W., Deshayes, L., and McGlauffin, M. (2006). Determination of parametric uncertainties for regression-based modeling of turning operations. *Transactions of NAMRI/SME*, 34.
- Kurdi, M. H., Haftka, R. T., Schmitz, T. L., and Mann, B. P. (November 5-11, 2005). A numerical study of uncertainty in stability and surface location error in high-speed milling. In *IMECE '05: Proceedings of the IMECE 2005*, number 80875. ASME.
- Michalewicz, Z., Dasgupta, D., Riche, R. L., and Schoenauer, M. (1996). Evolutionary algorithms for constrained engineering problems. *Computers & Industrial Engineering Journal*, 30(2):851–870.
- Nannen, V. and Eiben, A. (2006). A method for parameter calibration and relevance estimation in evolutionary algorithms. In *GECCO '06: Proceedings of the 8th annual conference on Genetic and evolutionary computation*, pages 183–190, New York, NY, USA. ACM Press.
- NIST/SEMATECH (2006). Nist/sematech engineering statistics handbook, <http://www.itl.nist.gov/div898/handbook/>.
- Raymer, M., Punch, W., Goodman, E., Kuhn, L., and Jain, A. (2000). Dimensionality reduction using genetic algorithms. *IEEE Trans. Evolutionary Computation*, 4:164–171.
- Rudenko, O., Schoenauer, M., Bosio, T., and Fontana, R. (Jan 2002). A multiobjective evolutionary algorithm for car front end design. *Lecture Notes in Computer Science*, 2310.
- Taylor, F. N. (1907). On the art of cutting metals. *Transactions of the ASME*, 28:31.
- Tukey, J. W. (1977). *Exploratory data analysis*. Addison-Wesley.
- Vigouroux, J., Deshayes, L., Fofou, S., and Welsch, L. (2007). An approach for optimization of machining parameters under uncertainties using intervals and evolutionary algorithms. In *Proceedings of the first International Conference on Smart Machining Systems, to appear*.
- Wang, X., Da, Z. J., Balaji, A. K., and Jawahir, I. S. (2002). Performance-based optimal selection of cutting conditions and cutting tools in multipass turning operations using genetic algorithms. *International Journal of Production Research*, 40(9):2053–2059.
- Yao, X. (1999). *Evolutionary Computation: Theory and Applications*. World Scientific.