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Which Value $\widetilde{x}$ Best Represents a Sample $x_1, \ldots, x_n$: Utility-Based Approach Under Interval Uncertainty

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Abstract. In many practical situations, we have several estimates $x_1, \ldots, x_n$ of the same quantity x. In such situations, it is desirable to combine this information into a single estimate $\widetilde{x}$. Often, the estimates x_i come with interval uncertainty, i.e., instead of the exact values x_i, we only know the intervals $[\underline{x}_i, \overline{x}_i]$ containing these values. In this paper, we formalize the problem of finding the combined estimate $\widetilde{x}$ as the problem of maximizing the corresponding utility, and we provide an efficient (quadratic-time) algorithm for computing the resulting estimate.

1 Which Value $\widetilde{x}$ Best Represents a Sample $x_1, \ldots, x_n$: Case of Exact Estimates

Need to combine several estimates. In many practical situations, we have several estimates $x_1, \ldots, x_n$ of the same quantity x. In such situations, it is often desirable to combine this information into a single estimate $\widetilde{x}$; see, e.g., [6].

Probabilistic case. If we know the probability distribution of the corresponding estimation errors $x_i - x$, then we can use known statistical techniques to find $\widetilde{x}$, e.g., we can use the Maximum Likelihood Method; see, e.g., [8].

Need to go beyond the probabilistic case. In many cases, however, we do not have any information about the corresponding probability distribution [6]. How can we then find $\widetilde{x}$?

Utility-based approach. According to the general decision theory, decisions of a rational person are equivalent to maximizing his/her *utility value* u; see, e.g., [1, 4, 5, 7]. Let us thus find the estimate $\widetilde{x}$ for which the utility $u(\widetilde{x})$ is the largest.

Our objective is to use a single value $\widetilde{x}$ instead of all n values x_i. For each i, the disutility $d = -u$ comes from the fact that if the actual estimate is x_i and we use a different value $\widetilde{x} \neq x_i$ instead, we are not doing an optimal thing. For example, if the optimal speed at which the car needs the least amount of fuel is x_i, and we instead run it at a speed $\widetilde{x} \neq x_i$, we thus waste some fuel.

For each i, the disutility d comes from the fact that the difference $\widetilde{x} - x_i$ is different from 0; there is no disutility if we use the actual value, so $d = d(\widetilde{x} - x_i)$ for an appropriate function $d(y)$, where $d(0) = 0$ and $d(y) > 0$ for $y \neq 0$.

The estimates are usually reasonably accurate, so the difference $x_i - \widetilde{x}$ is small, and we can expand the function $d(y)$ in Taylor series and keep only the first few terms in this expansion:

$$d(y) = d_0 + d_1 \cdot y + d_2 \cdot y^2 + \ldots$$

From $d(0) = 0$ we conclude that $d_0 = 0$. From $d(y) > 0$ for $y \neq 0$ we conclude that $d_1 = 0$ (else we would have $d(y) < 0$ for some small y) and $d_2 > 0$, so $d(y) = d_2 \cdot y^2 = d_2 \cdot (\widetilde{x} - x_i)^2$.

The overall disutility $d(\widetilde{x})$ of using $\widetilde{x}$ instead of each of the values $x_1, \ldots, x_n$ can be computed as the sum of the corresponding disutilities

$$d(\widetilde{x}) = \sum_{i=1}^{n} d(\widetilde{x} - x_i)^2 = d_2 \cdot \sum_{i=1}^{n} (\widetilde{x} - x_i)^2.$$

Maximizing utility $u(\widetilde{x}) \stackrel{\text{def}}{=} -d(\widetilde{x})$ is equivalent to minimizing disutility.

The resulting combined value. Since $d_2 > 0$, minimizing the disutility function function is equivalent to minimizing the re-scaled disutility function

$$D(\widetilde{x}) \stackrel{\text{def}}{=} \frac{d(\widetilde{x})}{d_2} = \sum_{i=1}^{n} (\widetilde{x} - x_i)^2.$$

Differentiating this expression with respect to $\widetilde{x}$ and equating the derivative to 0, we get

$$\widetilde{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i.$$

This is the well-known sample mean.

2 Case of Interval Uncertainty: Formulation of the Problem

Formulation of the practical problem. In many practical situations, instead of the exact estimates x_i, we only know the intervals $[\underline{x}_i, \overline{x}_i]$ that contain the unknown values x_i. How do we select the value x in this case?

Towards precise formulation of the problem. For different values x_i from the corresponding intervals $[\underline{x}_i, \overline{x}_i]$, we get, in general, different values of utility

$$U(\widetilde{x}, x_1, \ldots, x_n) = -D(\widetilde{x}, x_1, \ldots, x_n),$$

where $D(\widetilde{x}, x_1, \ldots, x_n) = \sum\limits_{i=1}^{n} (\widetilde{x} - x_i)^2$. Thus, all we know is that the actual (unknown) value of the utility belongs to the interval $[\underline{U}(\widetilde{x}), \overline{U}(\widetilde{x})] = [-\overline{D}(\widetilde{x}), -\underline{D}(\widetilde{x})]$, where

$$\underline{D}(\widetilde{x}) = \min D(\widetilde{x}, x_1, \ldots, x_n),$$

$$\overline{D}(\widetilde{x}) = \max D(\widetilde{x}, x_1, \ldots, x_n),$$

and min and max are taken over all possible combinations of values $x_i \in [\underline{x}_i, \overline{x}_i]$.

In such situations of interval uncertainty, decision making theory recommends using Hurwicz optimism-pessimism criterion [2–4], i.e., maximize the value

$$U(\widetilde{x}) \stackrel{\text{def}}{=} \alpha \cdot \overline{U}(\widetilde{x}) + (1 - \alpha) \cdot \underline{U}(\widetilde{x}),$$

where the parameter $\alpha \in [0, 1]$ describes the decision maker's degree of optimism. For $U = -D$, this is equivalent to minimizing the expression

$$D(\widetilde{x}) = -U(\widetilde{x}) = \alpha \cdot \underline{D}(\widetilde{x}) + (1 - \alpha) \cdot \overline{D}(\widetilde{x}).$$

What we do in this paper. In this paper, we describe an efficient algorithm for computing the value $\widetilde{x}$ that minimizes the resulting objective function $D(\widetilde{x})$.

3 Analysis of the Problem

Let us simplify the expressions for $\underline{D}(\widetilde{x})$, $\overline{D}(\widetilde{x})$, and $D(\widetilde{x})$. Each term $(\widetilde{x} - x_i)^2$ in the sum $D(\widetilde{x}, x_1, \ldots, x_n)$ depends only on its own variable x_i. Thus, with respect to x_i:

- the sum is the smallest when each of these terms is the smallest, and
- the sum is the largest when each term is the largest.

One can easily see that when x_i is in the $[\underline{x}_i, \overline{x}_i]$, the maximum of a term $(\widetilde{x} - x_i)^2$ is always attained at one of the interval's endpoints:

- at $x_i = \underline{x}_i$ when $\widetilde{x} \geq \widetilde{x}_i \stackrel{\text{def}}{=} \dfrac{\underline{x}_i + \overline{x}_i}{2}$ and
- at $x_i = \overline{x}_i$ when $\widetilde{x} < \widetilde{x}_i$.

Thus,

$$\overline{D}(\widetilde{x}) = \sum_{i:\widetilde{x} < \widetilde{x}_i} (\widetilde{x} - \overline{x}_i)^2 + \sum_{i:\widetilde{x} \geq \widetilde{x}_i} (\widetilde{x} - \underline{x}_i)^2.$$

Similarly, the minimum of the term $(\widetilde{x} - x_i)^2$ is attained:

- for $x_i = \widetilde{x}$ when $\widetilde{x} \in [\underline{x}_i, \overline{x}_i]$ (in this case, the minimum is 0);
- for $x_i = \underline{x}_i$ when $\widetilde{x} < \underline{x}_i$; and
- for $x_i = \overline{x}_i$ when $\widetilde{x} > \overline{x}_i$.

Thus,

$$\underline{D}(\widetilde{x}) = \sum_{i:\widetilde{x}>\overline{x}_i} (\widetilde{x} - \overline{x}_i)^2 + \sum_{i:\widetilde{x}<\underline{x}_i} (\widetilde{x} - \underline{x}_i)^2.$$

So, for $D(\widetilde{x}) = \alpha \cdot \underline{D}(\widetilde{x}) + (1-\alpha) \cdot \overline{D}(\widetilde{x})$, we get

$$D(\widetilde{x}) = \alpha \cdot \sum_{i:\widetilde{x}>\overline{x}_i} (\widetilde{x} - \overline{x}_i)^2 + \alpha \cdot \sum_{i:\widetilde{x}<\underline{x}_i} (\widetilde{x} - \underline{x}_i)^2 +$$

$$(1-\alpha) \cdot \sum_{i:\widetilde{x}<\widetilde{x}_i} (\widetilde{x} - \overline{x}_i)^2 + (1-\alpha) \cdot \sum_{i:\widetilde{x}\ge\widetilde{x}_i} (\widetilde{x} - \underline{x}_i)^2. \quad (1)$$

Towards an algorithm. The presence or absence of different values in the above expression depends on the relation of $\widetilde{x}$ with respect to the values $\underline{x}_i$, $\overline{x}_i$, and $\widetilde{x}_i$. Thus, if we sort these $3n$ values into a sequence $s_1 \le s_2 \le \ldots \le s_{3n}$, then on each interval $[s_j, s_{j+1}]$, the function $D(\widetilde{x})$ is simply a quadratic function of $\widetilde{x}$.

A quadratic function attains its minimum on an interval either at one of its midpoints, or at a point when the derivative is equal to 0 (if this point is inside the given interval). Differentiating the above expression for $D(\widetilde{x})$, equating the derivative to 0, dividing both sides by 0, and moving terms proportional not containing $\widetilde{x}$ to the right-hand side, we conclude that

$$(\alpha \cdot \#\{i : \widetilde{x} < \underline{x}_i \text{ or } \widetilde{x} > \overline{x}_i\} + 1 - \alpha) \cdot \widetilde{x} =$$

$$\alpha \cdot \sum_{i:\widetilde{x}>\overline{x}_i} \overline{x}_i + \alpha \cdot \sum_{i:\widetilde{x}<\underline{x}_i} \underline{x}_i + (1-\alpha) \cdot \sum_{i:\widetilde{x}<\widetilde{x}_i} \overline{x}_i + (1-\alpha) \cdot \sum_{i:\widetilde{x}\ge\widetilde{x}_i} \underline{x}_i.$$

Since s_j is a listing of all thresholds values $\underline{x}_i$, $\overline{x}_i$, and $\widetilde{x}_i$, then for $\widetilde{x} \in (s_j, s_{j+1})$, the inequality $\widetilde{x} < \underline{x}_i$ is equivalent to $s_{j+1} \le \underline{x}_i$. Similarly, the inequality $\widetilde{x} > \underline{x}_i$ is equivalent to $s_j \ge \overline{x}_i$. In general, for values $\widetilde{x} \in (s_j, s_{j+1})$, the above equation gets the form

$$(\alpha \cdot \#\{i : \widetilde{x} < \underline{x}_i \text{ or } \widetilde{x} > \overline{x}_i\} + 1 - \alpha) \cdot \widetilde{x} =$$

$$\alpha \cdot \sum_{i:s_j\ge\overline{x}_i} \overline{x}_i + \alpha \cdot \sum_{i:s_{j+1}\le\underline{x}_i} \underline{x}_i + (1-\alpha) \cdot \sum_{i:s_{j+1}\le\widetilde{x}_i} \overline{x}_i + (1-\alpha) \cdot \sum_{i:s_j\ge\widetilde{x}_i} \underline{x}_i.$$

From this equation, we can easily find the desired expression for the value $\widetilde{x}$ at which the derivative is 0.

Thus, we arrive at the following algorithm.

4 Resulting Algorithm

First, for each interval $[\underline{x}_i, \overline{x}_i]$, we compute its midpoint $\widetilde{x}_i = \dfrac{\underline{x}_i + \overline{x}_i}{2}$. Then, we sort the $3n$ values $\underline{x}_i$, $\overline{x}_i$, and $\widetilde{x}_i$ into an increasing sequence $s_1 \le s_2 \le \ldots \le s_{3n}$. To cover the whole real line, to these values, we add $s_0 = -\infty$ and $s_{3n+1} = +\infty$.

We compute the value of the objective function (1) on each of the endpoints $s_1, \ldots, s_{3n}$. Then, for each interval (s_i, s_{j+1}), we compute the value

$$\widetilde{x} = \frac{\alpha \cdot \sum\limits_{i: s_j \ge \overline{x}_i} \overline{x}_i + \alpha \cdot \sum\limits_{i: s_{j+1} \le \underline{x}_i} \underline{x}_i + (1-\alpha) \cdot \sum\limits_{i: s_{j+1} \le \widetilde{x}_i} \overline{x}_i + (1-\alpha) \cdot \sum\limits_{i: s_j \ge \widetilde{x}_i} \underline{x}_i}{\alpha \cdot \#\{i : \widetilde{x} < \underline{x}_i \text{ or } \widetilde{x} > \overline{x}_i\} + 1 - \alpha}.$$

If the resulting value $\widetilde{x}$ is within the interval (s_i, s_{j+1}), we compute the value of the objective function (1) corresponding to this $\widetilde{x}$.

After that, out of all the values $\widetilde{x}$ for which we have computed the value of the objective function (1), we return the value $\widetilde{x}$ for which objective function $D(\widetilde{x})$ was the smallest.

What is the computational complexity of this algorithm. Sorting $3n = O(n)$ values $\underline{x}_i$, $\overline{x}_i$, ad $\widetilde{x}_i$ takes time $O(n \cdot \ln(n))$.

Computing each value $d(\widetilde{x})$ of the objective function requires $O(n)$ computational steps. We compute $d(\widetilde{x})$ for $3n$ endpoints and for $\le 3n + 1$ values at which the derivative is 0 at each of the intervals (s_j, s_{j+1}) – for the total of $O(n)$ values.

Thus, overall, we need $O(n \cdot \ln(n)) + O(n) \cdot O(n) = O(n^2)$ computation steps. Hence, our algorithm runs in quadratic time.

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