The design of the spring wire straightening process is reflected in the straightening system. Straightening systems consist of a combination of straightening units that create constant material characteristics by adapting to the changing characteristics of the feed material. Every straightening unit and every straightening system has a specific straightening range, which is fixed by the spacing and the diameter of the straightening rolls. The straightening range $\Delta$ thus has limits for the minimal and maximal cross-sectional dimensions of material to be straightened. For round wires, for example, the relevant parameters are the minimum wire diameter $d_{\text{min}}$ and the maximum wire diameter $d_{\text{max}}$, as shown in Equation 1, below.

$$d_{\text{min}} \leq \Delta \leq d_{\text{max}}$$

Equation 1

Once the straightening range is fixed with due consideration to the material’s cross-sectional dimensions, the next step is to decide on the number of straightening rolls.

Given the difficulty of establishing the number of rolls by mathematical means, use is made of a knowledge base consisting of the linguistic terms (membership functions) of the input and output variables, a rule base, and the inference and defuzzifying mechanisms. The knowledge that is channeled into the fuzzy system (Figure 1, below) is the result of empirically established and verbally formulated rules. It is also based on the results of putting the virtual simulation of the straightening process to actual use.

Via the rule base, consisting of 25 rules, the input variables $\Delta r$ and $R_p$ are linked to the output variable $n$ (representing the number of straightening rolls). A sharply defined value for the input variable “radius of curvature range $\Delta r$” can be calculated via the rule base, consisting of 25 rules, the input variables $\Delta r$ and $R_p$ are linked to the output variable $n$ (representing the number of straightening rolls).
with Equation 2, below. The variables $r_{\text{max}}$ and $r_{\text{min}}$ are the maximal and minimal radius of curvature determined with Equation 2.

$$\Delta r = |r_{\text{max}} - r_{\text{min}}|$$  \hspace{1cm} \text{Equation 2}

The membership functions of the input variable yield point $R_p$ are laid down in Figure 2, page 53. The fuzziness is particularly evident in the overlapping of the variable sets. For example, an elongation limit $R_p = 800$ MPa at 33% (degree of membership $\mu = 0.33$) is assigned to the set very_small and at 67% (degree of membership $\mu = 0.67$) to the set small.

Use of a suitable inference mechanism and a specific defuzzifying method results finally in a specific conversion chart, as shown in Figure 3 on page 53, which can be used at any time to generate a sharply defined output variable for a set of sharply defined input variables. Table 1, above, presents derived values of $n$ (the number of straightening rolls) for a number of discrete values of the input variables $R_p$ (yield point) and $\Delta r$ (radius of curvature range).

In addition to the straightening range and number of straightening rollers, the way in which the straightening rolls are positioned has a major impact on the straightening process. After all, it is the positioning of the straightening rolls that influences the bending operations and, hence, the residual curvature.

Witels-Albert has developed various levels of technology, which differ in their degree of automation. In conventional straightening systems, simple tools are used to position the rolls. Another possibility is adjusting elements equipped with a position gauge or vernier scale. Advanced straightening technology featuring a high degree of automation, such as semiautomatic straightening units and systems (Figure 4, bottom left) or automatic roll actuators (Figure 5, above) can position the straightening rolls with reproducible high precision within a very short time. Software is a key component of the overall system at each of these two levels of technology. Whatever the degree of automation, Witels-Albert uses the SimDATA program (Figure 6, below) to determine the roll-adjustment values.

Marcus Paech is the technical managing director of Witels Apparate-Maschinen Albert GmbH, with headquarters in Berlin, Germany. Paech oversees product development, custom solutions, research, sales, service, and daily operations. Readers may contact him by phone at +49 (0)30 723 988 0 or e-mail at info@witels-albert.com.

**Figure 4:** Semi-automatic straightening system.

**Figure 5:** Automatic roll actuators.

**Figure 6:** SimDATA software determines roll-adjustment values.

<table>
<thead>
<tr>
<th>Range of initial curvature radius $\Delta r$ [mm]</th>
<th>Yield point $R_p$ [MPa]</th>
<th>Number of straightening rolls $n$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>1000</td>
<td>7</td>
</tr>
<tr>
<td>100</td>
<td>1000</td>
<td>9</td>
</tr>
<tr>
<td>100</td>
<td>2000</td>
<td>11</td>
</tr>
<tr>
<td>160</td>
<td>2000</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 1: Values for the number of straightening rolls $n$ calculated with fuzzy logic.