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Fuzzy Evolving Networks and Fuzzy Regression Analysis for Two-Modal Regulatory Systems – Prediction Strategies for Fuzzy Target-Environment Networks

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Abstract. Target-environment networks provide a conceptual framework for the analysis and prediction of complex regulatory systems such as genetic networks, eco-finance networks or sensor-target assignments. These evolving networks consist of two major groups of entities that are interacting by unknown relationships. The structure and dynamics of the hidden regulatory system have to be revealed from uncertain measurement data. In this paper, the concept of fuzzy target-environment networks is introduced and various fuzzy possibilistic regression models are presented. The relation between the targets and/or environmental entities of the regulatory network is given in terms of a fuzzy model. The vagueness of the regulatory system results from the (unknown) fuzzy coefficients. For an identification of the shape of the fuzzy coefficients methods from fuzzy regression are adapted and made applicable to the bi-level situation of target-environment networks and uncertain data. Various shapes of fuzzy coefficients are considered and the control of outliers is discussed. The paper ends with a conclusion and an outlook to future studies.

Keywords. Fuzzy evolving networks, fuzzy target-environment networks, uncertainty, fuzzy theory, fuzzy regression analysis, possibilistic regression

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1 Introduction

In our hyper-connected world, *interdependent networks* are of significant importance in the modelling and prediction of regulatory systems. Interconnected networks with multiple connected groups of entities arise in many applications ranging from the prediction of genetic regulatory patterns in computational biology and the modelling and simulation of eco-finance networks to the formation of multisensor-multitarget networks in NBC-tracking scenarios. In this paper, we are focussing on the important group of so-called *target-environment networks under uncertainty* [15]. These *two-modal regulatory systems* are composed of two distinct groups of data which define different but strongly related levels of the model. The first group comprises the entities or *targets* under observation, which clearly are the most important variables of the regulatory system. The second group consists of a certain number of additional *environmental factors* that can have a strong impact on the targets regulatory patterns. The hidden interactions between the entities of the system have to be revealed from measurement data. Here, data uncertainty plays an important role with regard to modelling and prediction of the future states of the two-modal regulatory system.

An important example of two-modal regulatory systems are the so-called *gene-environment networks*, which were introduced in the genetic context by Weber et al. [4, 6, 29, 30, 31, 32, 36, 37, 38, 45]. Here, the expression values of genes or proteins are the target variables under consideration. Additional environmental factors like toxins, transcription factors or other components of the metabolic pathways may take a strong influence on the targets. Since microarray experiments as well as environmental observations usually result in uncertain data, this approach has been further extended in order to deal with errors and data uncertainty. The papers [33, 39, 40, 41, 42, 43, 44] focus on gene-environment networks where noise and uncertainty are represented in terms *error intervals*. For an estimation of the unknown system parameters, a *regression analysis* based on *interval-arithmetics* is applied leading to *generalized Chebychev approximation problems* and regression problems to be solved by methods of *generalized semi-infinite optimization* [34, 35]. Recently, gene-environment networks under *ellipsoidal uncertainty* have been introduced in [13, 14, 15, 16]. In this approach, functionally related groups of variables are identified with data mining methods and the uncertain states of targets and environmental clusters are represented in terms of ellipsoids. An affine-linear model based on *ellipsoidal calculus* is applied to predict the future ellipsoidal states of the system and the estimation of system parameters is based on a *set-theoretic regression analysis*.

In the last decade, the concept of target-environment networks has been continuously developed and now provides a conceptual framework for many regulatory systems in computational biology and life sciences. In addition, *target-environment networks* have also been applied to financial sciences, where so-called *eco-finance networks* are introduced in [12, 40].

The condition of the regression models depends heavily on the quality of the available data sets. For example, modern high-throughput technologies can be used to measure the expression profiles of a large number of genes simultaneously, but at a limited number of reading points. *Regression analysis* can be applied to identify the functional relationship between independent and dependent variables, where both variables are given as real numbers [7]. Nevertheless, for classical regression analysis, measurements have to be taken at a high number of reading points in order to obtain valid statistical relations between the dependent and independent variables, which can be considered as too expensive in the genetic context. In addition, in classical regression analysis the linearity assumption has to be fulfilled, so that gene-environment networks are clearly out of the scope of classical regression.

In situations where these assumptions are not fulfilled, where imprecise data with not normally distributed errors have to be considered or where a vagueness in the relationship between input and output variables exists, *fuzzy-regression analysis* offers a more general viewpoint and provides means for tackling problems failing to satisfy these assumptions. Unlike classical regression, deviations between observed values and estimated values are assumed to be due to *system fuzziness* or *fuzziness of regression coefficients* [3].

In this paper, we introduce the new concept of *fuzzy target-environment networks* and discuss the related fuzzy regression models. The vagueness of the relation between the targets and/or environmental factors of such a regulatory network results from the (unknown) fuzzy coefficients of the underlying *fuzzy model* and it is no longer determined by precise crisp coefficients. For an identification of the shape of the fuzzy coefficients, methods from fuzzy regression have to be adapted and made applicable to the bi-level situation of target-environment systems and data.

Fuzzy regression as a variation of classical regression has been studied by many authors and we refer to [9] for a recent literature review on fuzzy regression approaches and applications. In general, there are two types of fuzzy regression methods - *possibilistic regression*, which is based on Tanaka's linear programming approach [28] and *fuzzy least-squares regression* [5]. In this paper, we focus on possibilistic regression and adapt various extensions of the *fuzzy regression problem* introduced by Tanaka et al. [28]. This model was based on crisp input vectors as well as fuzzy output vectors and used fuzzy coefficients, which were represented by symmetric triangular fuzzy numbers. The underlying idea was to minimize the fuzziness of the model by minimizing the spread of the fuzzy output or the total support of the fuzzy coefficients subject to all the given data. This basic model has been further extended in several directions in order to deal with potential limitations of possibilistic regression. For example, in possibilistic regression based on symmetric triangular fuzzy numbers, only the extremal data points determine the structure of the model. All others data points have no impact on the structure what results in a high sensitivity to outliers [20, 21].

This problem can be resolved by using asymmetric triangular or trapezoidal fuzzy numbers [2, 8]. Since Tanaka et al. have introduced the concept of fuzzy regression, several fuzzy regression approaches have been proposed, often referring to a particular nature of input-output data. Some authors focus on crisp input-crisp output data [22], others use mixed crisp input-fuzzy output data [28] or fuzzy input-fuzzy output data [23]. Although possibilistic regression has been successfully applied in many areas of engineering sciences and Operations Research, methods involving fuzzy concepts have been rarely applied to genetics [1].

In this study, we consider fuzzy possibilistic regression for target-environment networks affected by errors and uncertainty. We present various fuzzy regression algorithms for target-environment data based on different representations of the fuzzy coefficients of the underlying fuzzy model. The algorithms are applied to crisp input-crisp output data. In addition, by assigning individual membership grades to input-output samples, the influence of outliers can be softened and controlled.

The paper is organized as follows: In Section 2, the concept of fuzzy target-environ- ment networks and the corresponding fuzzy regression model with fuzzy coefficients are introduced. In Section 3, we adapt Tanaka's possibilistic regression model for crisp target-environment data and introduce various fuzzy regression algorithms. To overcome the limitations of this approach, we consider different shapes of fuzzy coefficients in terms of symmetric and asymmetric triangular fuzzy sets as well as symmetric and asymmetric trapezoidal fuzzy numbers. In addition, we consider models where membership grades are assigned to input-output data in order to deal with outliers. Finally, in Section 4, we conclude with an outlook on potential directions of research.

2 Fuzzy Target-Environment Networks and Fuzzy Regression

In this section, the concept of *fuzzy target-environment networks* is introduced. A *linear fuzzy model* determines the synergistic connections between the targets and the additional environmental entities. Various algorithms for an estimation of the unknown fuzzy coefficients of the fuzzy model are discussed in Section 3.

2.1 The Fuzzy Model

Target-environment networks and their inherent dynamics are often modeled by time-discrete systems

$$X^{(k+1)} = F\big(X^{(k)}, E^{(k)}\big),$$
$$E^{(k+1)} = G\big(X^{(k)}, E^{(k)}\big),$$

for $k \geq 0$, where the time-dependent n-vector $X^{(k)} = (X_1^{(k)}, \ldots, X_n^{(k)})^T$ denotes the expression values of the n targets and the m-vector $E = (E_1^{(k)}, \ldots, E_m^{(k)})^T$ represents the values of the m environmental items. Both linear and nonlinear models are available, where $F : \mathbb{R}^{n+m} \to \mathbb{R}^n$ and $G : \mathbb{R}^{n+m} \to \mathbb{R}^m$ describe the linear or nonlinear dynamics of the system.

In this paper, we focus on the linear dynamics of single targets and environmental items. The time-discrete dynamics of each target, X_j $(j = 1,\ldots,n)$, is represented by a $(n+m)$-input and single-output linear fuzzy system

$$X_j^{(k+1)} := \mathscr{F}_j\big(X^{(k)}, E^{(k)}\big) = Z_{j0} + \sum_{r=1}^{n} A_{jr} X_r^{(k)} + \sum_{s=1}^{m} B_{js} E_s^{(k)} \quad (k \in \mathbb{N}_0).$$

Similarly, the states of the environmental items, E_i $(i = 1,\ldots,m)$, are given by

$$E_i^{(k+1)} := \mathscr{G}_i\big(X^{(k)}, E^{(k)}\big) = Z'_{i0} + \sum_{r=1}^{n} A'_{ir} X_r^{(k)} + \sum_{s=1}^{m} B'_{is} E_s^{(k)} \quad (k \in \mathbb{N}_0).$$

The unknown fuzzy coefficients $Z_{j0}, A_{jr}, B_{js}, Z'_{i0}, A'_{ir}, B'_{is}$ of the fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$ have to be determined from *crisp data vectors*

$$\overline{\mathbb{X}}^{(\kappa)} = \big(\overline{X}_1^{(\kappa)}, \ldots, \overline{X}_n^{(\kappa)}\big)^T \quad \text{and} \quad \overline{\mathbb{E}}^{(\kappa)} = \big(\overline{E}_1^{(\kappa)}, \ldots, \overline{E}_m^{(\kappa)}\big)^T,$$

with $\kappa = 0,1,\ldots,T+1$, obtained from measurements taken at reading points $t_0 < t_1 < \ldots < t_{T+1}$. For the initial states of the linear fuzzy system we assume $X_r^{(0)} = \overline{X}_r^{(0)}$ and $E_s^{(0)} = \overline{E}_s^{(0)}$ $(r = 1,\ldots,n;\ s = 1,\ldots,m)$.

2.2 Fuzzy Target-Environment Networks

The uncertain relations between the targets and environmental factors of the fuzzy model can be represented in terms of a highly interconnected regulatory network (cf. Fig. 1). The nodes of this *fuzzy target-environment network* are given by the targets and environmental items. The branches between targets and/or environmental factors are weighted by the corresponding fuzzy coefficients that define the coupling rules of the fuzzy model. In order to include the intercepts Z_{j0} and Z'_{i0} in our network, we introduce an additional node **0**. We note that also weights can be assigned to the nodes of the fuzzy network. This can be, e.g., the outputs (or some measure of the outputs) of the fuzzy model. Although the weights of the branches are static, the evolution of the states of the targets and environmental items turns the system into a time-dependent *fuzzy evolving network*. Hereby, fuzzy-discrete mathematics and its network algorithms in both versions, statically and dynamically, becomes applicable on subjects such as connectedness, components, clusters, cycles, shortest paths or further subnetworks [11, 17]. Beside these discrete-combinatorial aspects, combinatorial relations between graphs and (nonlinear) optimization problems as well as topological properties of regulatory networks can be analyzed.

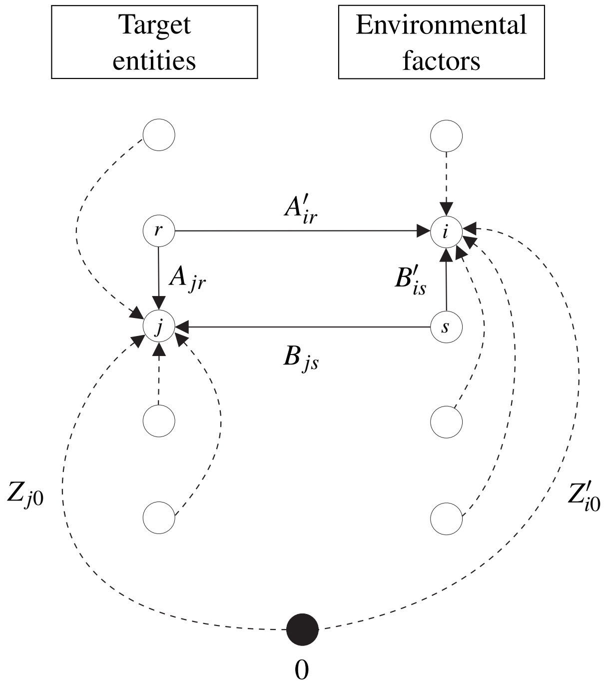

Figure 1: The fuzzy target-environment network. The nodes are the targets and environmental factors. The branches are weighted by the fuzzy coefficients of the fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$.

2.3 Fuzzy Regression

The basic idea of fuzzy regression is to minimize the fuzziness of the fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$. In case of *non-fuzzy data* they have to include all the given input-output data in their *level sets*[4], i.e.,

$$\overline{X}_j^{(\kappa+1)} \in \left[\mathscr{F}_j\left(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\right)\right]_{\alpha}, \; \overline{E}_i^{(\kappa+1)} \in \left[\mathscr{G}_i\left(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\right)\right]_{\alpha'} \quad (\kappa = 0, 1, \dots, T).$$

The *inclusion relations* for target and environmental data sets depend on the level sets of the fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$ with parameters $\alpha, \alpha' \in (0,1]$, which have to be given by the practitioner according to the desired spread of the fuzzy models. They are usually unequal what refers to the individual behaviour of the two distinct groups of data.

In the following sections, we introduce various *fuzzy regression models* for fuzzy target-environment networks. These models are based on crisp measurement data as well as many different kinds of fuzzy coefficients.

[4]The *r-level* (or *r-cut*) of a fuzzy set $\mu : \mathbb{R} \to [0,1]$ is defined for $0 < r \leq 1$ as the set $[\mu]_r := \{x \in \mathbb{R} \,|\, \mu(x) \geq r\}$.

3 Fuzzy Regression Analysis for Target-Environment Data

In this section, we focus on fuzzy regression models for non-fuzzy target-environment data. The fuzzy coefficients of the linear fuzzy models $\mathscr{F}$ and $\mathscr{G}$ have to be determined from *non-fuzzy input* data vectors

$$\overline{\mathbb{X}}^{(\kappa)} = \left(\overline{X}_1^{(\kappa)}, \ldots, \overline{X}_n^{(\kappa)}\right)^T \in \mathbb{R}^n \quad \text{and} \quad \overline{\mathbb{E}}^{(\kappa)} = \left(\overline{E}_1^{(\kappa)}, \ldots, \overline{E}_m^{(\kappa)}\right)^T \in \mathbb{R}^m,$$

with $\kappa = 0, 1, \ldots, T+1$.

3.1 Fuzzy Regression Based on Symmetric Triangular Fuzzy Coefficients

In the first fuzzy regression model, the coefficients of the fuzzy model are given by *symmetric triangular fuzzy numbers*. As we are interested in the dynamics of single targets and environmental factors, our regression analysis will be based on crisp data sets

$$\left(\left(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\right)^T ; \overline{X}_j^{(\kappa+1)}\right), \; \left(\left(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\right)^T ; \overline{E}_i^{(\kappa+1)}\right) \quad (\kappa = 0, 1, \ldots, T).$$

The symmetric triangular fuzzy coefficients can be represented in terms of their center (C) and width (W) (cf. Fig. 2):

$$\begin{aligned} Z_{j0} &= (Z_{j0}^C, Z_{j0}^W)^T, \; A_{jr} = (A_{jr}^C, A_{jr}^W)^T, \; B_{js} = (B_{js}^C, B_{js}^W)^T, \\ Z'_{i0} &= (Z'^C_{i0}, Z'^W_{i0})^T, \; A'_{ir} = (A'^C_{ir}, A'^W_{ir})^T, \; B'_{is} = (B'^C_{is}, B'^W_{is})^T. \end{aligned}$$

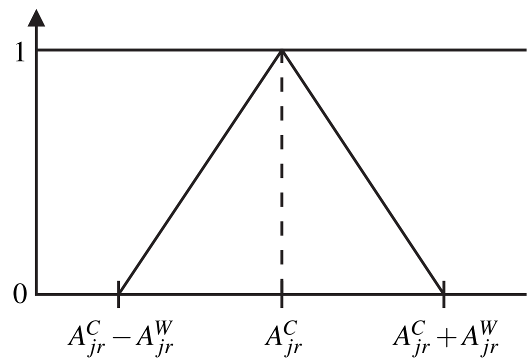

Figure 2: The symmetric triangular fuzzy coefficient $A_{jr} = (A_{jr}^C, A_{jr}^W)^T$.

Applying interval arithmetics [10], the fuzzy model $\mathscr{F}_j$ can be rewritten as

$$\begin{aligned}
&\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)\\
&= Z_{j0} + \sum_{r=1}^{n} A_{jr}X_r^{(k)} + \sum_{s=1}^{m} B_{js}E_s^{(k)}\\
&= (Z_{j0}^C, Z_{j0}^W)^T + \sum_{r=1}^{n} (A_{jr}^C, A_{jr}^W)^T X_r^{(k)} + \sum_{s=1}^{m} (B_{js}^C, B_{js}^W)^T E_s^{(k)}\\
&= \left(Z_{j0}^C + \sum_{r=1}^{n} A_{jr}^C \cdot X_r^{(k)} + \sum_{s=1}^{m} B_{js}^C \cdot E_s^{(k)}, Z_{j0}^W + \sum_{r=1}^{n} A_{jr}^W \cdot \big|X_r^{(k)}\big| + \sum_{s=1}^{m} B_{js}^W \cdot \big|E_s^{(k)}\big| \right)^T.
\end{aligned}$$

Thus, $\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)$ is a symmetric triangular fuzzy number

$$\mathscr{F}_j\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big), \mathscr{F}_j^W\big(X^{(k)},E^{(k)}\big)\big)^T$$

with

$$\begin{aligned}
\mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) &= Z_{j0}^C + \sum_{r=1}^{n} A_{jr}^C \cdot X_r^{(k)} + \sum_{s=1}^{m} B_{js}^C \cdot E_s^{(k)},\\
\mathscr{F}^W\big(X^{(k)},E^{(k)}\big) &= Z_{j0}^W + \sum_{r=1}^{n} A_{jr}^W \cdot \big|X_r^{(k)}\big| + \sum_{s=1}^{m} B_{js}^W \cdot \big|E_s^{(k)}\big|.
\end{aligned}$$

Similarly, the fuzzy model $\mathscr{G}$ can be represented as the symmetric triangular fuzzy number

$$\mathscr{G}_i\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big), \mathscr{G}_i^W\big(X^{(k)},E^{(k)}\big)\big)^T,$$

where

$$\begin{aligned}
\mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big) &= Z_{i0}'^C + \sum_{r=1}^{n} A_{ir}'^C \cdot X_r^{(k)} + \sum_{s=1}^{m} B_{is}'^C \cdot E_s^{(k)},\\
\mathscr{G}_i^W\big(X^{(k)},E^{(k)}\big) &= Z_{i0}'^W + \sum_{r=1}^{n} A_{ir}'^W \cdot \big|X_r^{(k)}\big| + \sum_{s=1}^{m} B_{is}'^W \cdot \big|E_s^{(k)}\big|.
\end{aligned}$$

According to the basic idea of fuzzy regression, we have to determine fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$ which include all the given input-output sets $\big(\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big)^T;\overline{X}_j^{(\kappa+1)}\big)$ and $\big(\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big)^T;\overline{E}_i^{(\kappa+1)}\big)$ in their level sets. The α-cut of $\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)$ with $\alpha \in (0,1]$ as depicted in Fig. 3 is given by the interval

$$\big[\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)\big]_\alpha = \big[\mathscr{F}_{j\alpha}^L\big(X^{(k)},E^{(k)}\big), \mathscr{F}_{j\alpha}^R\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\begin{aligned}
\mathscr{F}_{j\alpha}^L\big(X^{(k)},E^{(k)}\big) &= \mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) - (1-\alpha)\cdot \mathscr{F}_j^W\big(X^{(k)},E^{(k)}\big),\\
\mathscr{F}_{j\alpha}^R\big(X^{(k)},E^{(k)}\big) &= \mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) + (1-\alpha)\cdot \mathscr{F}_j^W\big(X^{(k)},E^{(k)}\big).
\end{aligned}$$

Similarly, the α'-cut of $\mathscr{G}_i\big(X^{(k)},E^{(k)}\big)$ with $\alpha' \in (0,1]$ takes the form

$$\big[\mathscr{G}_i\big(X^{(k)},E^{(k)}\big)\big]_{\alpha'} = \big[\mathscr{G}^L_{i\alpha'}\big(X^{(k)},E^{(k)}\big),\, \mathscr{G}^R_{i\alpha'}\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\begin{aligned}\mathscr{G}^L_{i\alpha'}\big(X^{(k)},E^{(k)}\big) &= \mathscr{G}^C_i\big(X^{(k)},E^{(k)}\big) - (1-\alpha')\cdot \mathscr{G}^W_i\big(X^{(k)},E^{(k)}\big),\\ \mathscr{G}^R_{i\alpha'}\big(X^{(k)},E^{(k)}\big) &= \mathscr{G}^C_i\big(X^{(k)},E^{(k)}\big) + (1-\alpha')\cdot \mathscr{G}^W_i\big(X^{(k)},E^{(k)}\big).\end{aligned}$$

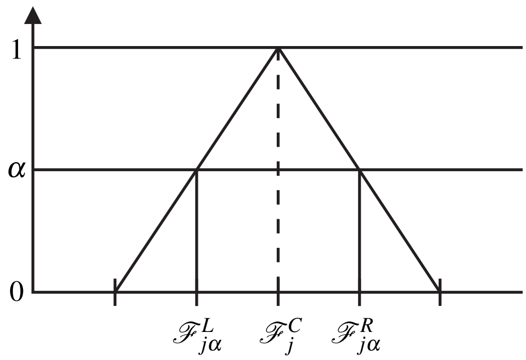

Figure 3: The α-cut of the fuzzy model $\mathscr{F}_j$.

Therefore, the states $\overline{X}_j^{(\kappa+1)}$ and $\overline{E}_i^{(\kappa+1)}$ have to fulfill the constraints

$$\begin{aligned}\mathscr{F}^L_{j\alpha}\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big) &\le \overline{X}_j^{(\kappa+1)} \le \mathscr{F}^R_{j\alpha}\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big),\\ \mathscr{G}^L_{i\alpha'}\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big) &\le \overline{E}_i^{(\kappa+1)} \le \mathscr{G}^R_{i\alpha'}\big(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\big),\end{aligned}$$

for all $\kappa \in \{0,1,\ldots,T\}$. As mentioned before, the inclusion relations for target and environmental data sets depend on level sets with (unequal) parameters $\alpha, \alpha' \in (0,1]$. We introduce also some additional conditions on the size of the coefficients of the fuzzy models. The constraints

$$Z^W_{j0}, A^W_{jr}, B^W_{js}, Z'^W_{i0}, A'^W_{ir}, B'^W_{is} \ge 0$$

ensure that the spread of a fuzzy coefficient is non-negative.

Now, we introduce two linear regression models for determining the symmetric triangular fuzzy coefficients of the linear fuzzy model $\mathscr{F}_j$ and $\mathscr{G}_i$. The first model is based on the idea used in [28]. The parameters are determined by solving a linear programming problem with an objective function of minimizing the total spread of the fuzzy coefficients:

Fuzzy-Regression for Target-Environment Data (FR 1)

$$\text{Minimize} \quad \sum_{j=1}^{n}\left(Z_{j0}^{W}+\sum_{r=1}^{n}A_{jr}^{W}+\sum_{s=1}^{m}B_{js}^{W}\right)+\sum_{i=1}^{m}\left(Z_{i0}^{\prime W}+\sum_{r=1}^{n}A_{ir}^{\prime W}+\sum_{s=1}^{m}B_{is}^{\prime W}\right),$$

$$\begin{aligned}
\text{subject to} \quad & \mathscr{F}_{j\alpha}^{L}\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) \le \overline{X}_j^{(\kappa+1)} \le \mathscr{F}_{j\alpha}^{R}\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right),\\
& \mathscr{G}_{i\alpha'}^{L}\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) \le \overline{E}_i^{(\kappa+1)} \le \mathscr{G}_{i\alpha'}^{R}\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\\
& (j=1,\ldots,n;\ i=1,\ldots,m;\ \kappa=0,1,\ldots,T),\\
& Z_{j0}^{W}, Z_{i0}^{\prime W} \ge 0,\\
& A_{jr}^{W}, A_{ir}^{\prime W} \ge 0\ (r=1,\ldots,n),\\
& B_{js}^{W}, B_{is}^{\prime W} \ge 0\ (s=1,\ldots,m)\\
& (j=1,\ldots,n;\ i=1,\ldots,m).
\end{aligned}$$

Example 1

In this illustrative example we consider a time-discrete regulatory model with two target and two environmental factors:

$$\begin{aligned}
X_1^{(\kappa+1)} &= 0.25X_1^{(\kappa)}+0.55X_2^{(\kappa)}+0.20E_1^{(\kappa)}+0.45E_2^{(\kappa)},\\
X_2^{(\kappa+1)} &= 0.25X_1^{(\kappa)}+0.65X_2^{(\kappa)}-0.30E_1^{(\kappa)}+0.40E_2^{(\kappa)},\\
E_1^{(\kappa+1)} &= 0.30X_1^{(\kappa)}+0.25X_2^{(\kappa)}+0.70E_1^{(\kappa)}+0.30E_2^{(\kappa)},\\
E_2^{(\kappa+1)} &= -0.35X_1^{(\kappa)}+0.50X_2^{(\kappa)}+0.50E_1^{(\kappa)}+0.30E_2^{(\kappa)}.
\end{aligned}$$

The crisp initial values are $X_1^{(0)}=-0.50$, $X_2^{(0)}=-0.75$, $E_1^{(0)}=-0.50$, $E_2^{(0)}=-0.45$. Table 1 shows the first six observations of the target and environmental factors:

Table 1: Measurements of targets and environmental factors.

κ	0	1	2	3	4	5
$X_1^{(\kappa)}$	−0.5000	−1.0504	−1.2092	−1.3274	−1.4365	−1.5367
$X_2^{(\kappa)}$	−0.7500	−0.7434	−0.7019	−0.6202	−0.5527	−0.4995
$E_1^{(\kappa)}$	−0.5000	−1.0922	−1.4784	−1.8020	−2.0834	−2.3321
$E_2^{(\kappa)}$	0.4500	−0.7095	−0.7630	−0.8958	−1.0153	−1.1199

By applying algorithm FR1 with symmetric fuzzy numbers to this data set, we obtain the results displayed in Fig. 4 (red = original model; fuzzy predictions: blue = center - width, green = center + width). The prediction follows the general trend of the original model. However, a relatively large error is obtained for the second environmental factor (d) which is due to the fact that only extremal data points determine the structure of the fuzzy model.

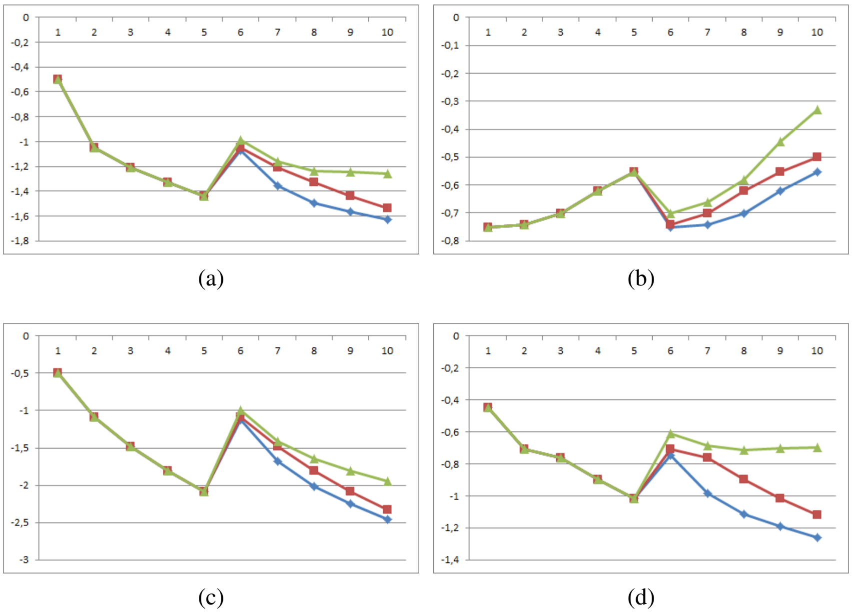

Figure 4: Results of the fuzzy-regression algorithm FR1 for (a) first target, (b) second target, (c) first environmental factor and (d) second environmental factor.

Other objective functions for fuzzy regression are given in the literature. For example, the total spread of the fuzzy outputs can be used to define an alternative objective function (cf. [8, 26, 27, 28]). In our model, such kind of objective functions are given by

$$\sum_{\kappa=0}^{T}\left\{\sum_{j=0}^{n}\mathscr{F}_j^W\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)+\sum_{i=0}^{m}\mathscr{G}_i^W\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\right\},$$

and we obtain the following regression problem:

Fuzzy-Regression for Target-Environment Data (FR 2)

Minimize
$$\sum_{\kappa=0}^{T}\left\{\sum_{j=1}^{n}\left(Z_{j0}^{W}+\sum_{r=1}^{n}A_{jr}^{W}\cdot|\overline{X}_r^{(\kappa)}|+\sum_{s=1}^{m}B_{js}^{W}\cdot|\overline{E}_s^{(\kappa)}|\right)\right.$$
$$\left.+\sum_{i=1}^{m}\left(Z_{i0}^{\prime W}+\sum_{r=1}^{n}A_{ir}^{\prime W}\cdot|\overline{X}_r^{(\kappa)}|+\sum_{s=1}^{m}B_{is}^{\prime W}\cdot|\overline{E}_s^{(\kappa)}|\right)\right\}$$

subject to
$$\mathscr{F}_{j\alpha}^{L}(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)})\leq\overline{X}_j^{(\kappa+1)}\leq\mathscr{F}_{j\alpha}^{R}(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}),$$
$$\mathscr{G}_{i\alpha'}^{L}(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)})\leq\overline{E}_i^{(\kappa+1)}\leq\mathscr{G}_{i\alpha'}^{R}(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)})$$
$$(j=1,\ldots,n;\ i=1,\ldots,m;\ \kappa=0,1,\ldots,T),$$

$$Z_{j0}^{W},Z_{i0}^{\prime W}\geq 0,$$
$$A_{jr}^{W},A_{ir}^{\prime W}\geq 0,(r=1,\ldots,n),$$
$$B_{js}^{W},B_{is}^{\prime W}\geq 0,(s=1,\ldots,m)$$
$$(j=1,\ldots,n;\ i=1,\ldots,m).$$

Example 2

For the data from Example 1, algorithm FR2 leads to the results shown in Fig. 5. Here, the sum of spreads of the fuzzy outputs is minimized and the width of the predictions is significantly smaller compared to the results from Example 1 (red = original model; fuzzy predictions: blue = center - width, green = center + width).

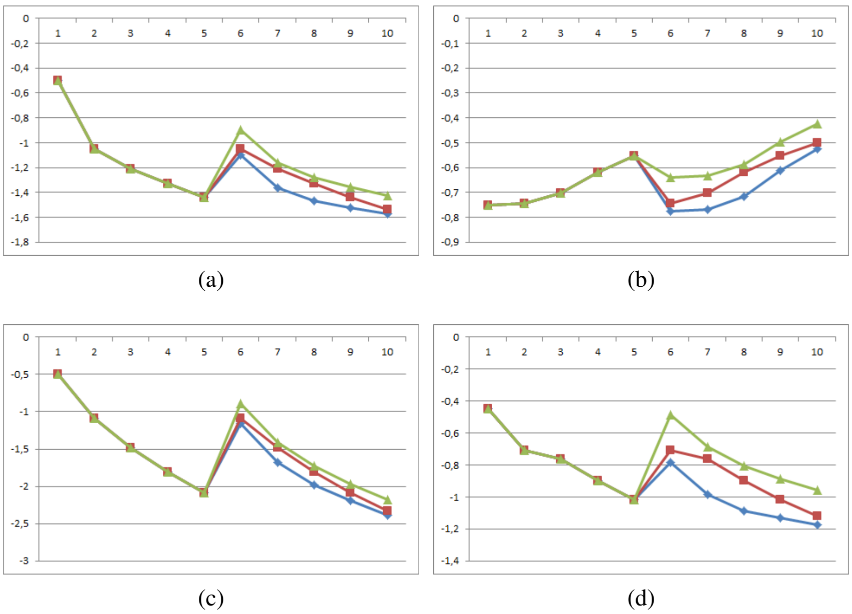

Figure 5: Results of the fuzzy-regression algorithm FR2 for (a) first target, (b) second target, (c) first environmental factor and (d) second environmental factor.

3.2 Fuzzy Regression Based on Symmetric Triangular Fuzzy Coefficients with Membership Grades

Data sets obtained by experiments (e.g., microarray data) and environmental measurements are always affected by noise and uncertainty. In a preprocessing step, a statistical analysis of the measurement values can be performed in order to guarantee the quality of the observed data. In particular, outliers have to be detected and deleted from the sample. However, it is not always possible to split this sample unambiguously. For this reason membership grades $\alpha_{j\kappa}, \alpha'_{i\kappa} \in (0,1]$ are assigned to the data sets

$$\Big(\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big)^T; \overline{X}_j^{(\kappa+1)}\Big) \quad \text{and} \quad \Big(\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big)^T; \overline{E}_i^{(\kappa+1)}\Big) \quad (\kappa = 0, 1, \ldots, T).$$

When we include the membership grades in the objective function and the inclusion relations of the linear fuzzy regression model (FR2), we obtain the following method:

Fuzzy-Regression for Target-Environment Data (FR 3)

Minimize
$$\sum_{\kappa=0}^{T} \Bigg\{ \sum_{j=1}^{n} \alpha_{j\kappa} \cdot \Big(Z_{j0}^{W} + \sum_{r=1}^{n} A_{jr}^{W} \cdot \big|\overline{X}_r^{(\kappa)}\big| + \sum_{s=1}^{m} B_{js}^{W} \cdot \big|\overline{E}_s^{(\kappa)}\big| \Big) + \sum_{i=1}^{m} \alpha'_{i\kappa} \cdot \Big(Z_{i0}^{\prime W} + \sum_{r=1}^{n} A_{ir}^{\prime W} \cdot \big|\overline{X}_r^{(\kappa)}\big| + \sum_{s=1}^{m} B_{is}^{\prime W} \cdot \big|\overline{E}_s^{(\kappa)}\big| \Big) \Bigg\}$$

subject to
$$\mathscr{F}^{L}_{j\,\alpha_{j\kappa}}\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \le \overline{X}_j^{(\kappa+1)} \le \mathscr{F}^{R}_{j\,\alpha_{j\kappa}}\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big),$$
$$\mathscr{G}^{L}_{i\,\alpha'_{i\kappa}}\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \le \overline{E}_i^{(\kappa+1)} \le \mathscr{G}^{R}_{i\,\alpha'_{i\kappa}}\big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big)$$
$$(j = 1, \ldots, n;\ i = 1, \ldots, m;\ \kappa = 0, 1, \ldots, T),$$

$$Z_{j0}^{W}, Z_{i0}^{\prime W} \ge 0,$$
$$A_{jr}^{W}, A_{ir}^{\prime W} \ge 0\ (r = 1, \ldots, n),$$
$$B_{js}^{W}, B_{is}^{\prime W} \ge 0\ (s = 1, \ldots, m)$$
$$(j = 1, \ldots, n;\ i = 1, \ldots, m).$$

3.3 Fuzzy Regression Based on Asymmetric Triangular Fuzzy Coefficients

Limitations of fuzzy regression models based on symmetric triangular fuzzy coefficients were pointed out in [8]. One major drawback is that obviously different data sets may lead to the same linear fuzzy model. This is due to the fact that extremal data points mainly determine the spread of the models $\mathscr{F}_j$ and $\mathscr{G}_i$. As linear fuzzy regression models with symmetric triangular fuzzy coefficients are not flexible enough to represent the difference between data sets, Ishibuchi and Nii proposed *asymmetric triangular* or *trapezoidal fuzzy coefficients* [8]. In this section, we adapt this approach for a regression analysis of target-environment data based on asymmetric triangular fuzzy numbers. An algorithm for trapezoidal fuzzy coefficients is presented in Section 3.4.

We now assume that the coefficients of the fuzzy regression model are *asymmetric triangular fuzzy coefficients* (cf. Fig. 6). Therefore, they can be represented in terms of their lower limit (L), center (C) and upper limit (U) as follows:

$$Z_{j0} = (Z_{j0}^L, Z_{j0}^C, Z_{j0}^U)^T, \quad A_{jr} = (A_{jr}^L, A_{jr}^C, A_{jr}^U)^T, \quad B_{js} = (B_{js}^L, B_{js}^C, B_{js}^U)^T,$$
$$Z'_{i0} = (Z_{i0}'^L, Z_{i0}'^C, Z_{i0}'^U)^T, \quad A'_{ir} = (A_{ir}'^L, A_{ir}'^C, A_{ir}'^U)^T, \quad B'_{is} = (B_{is}'^L, B_{is}'^C, B_{is}'^U)^T,$$

where $r = 1, \ldots, n$ and $s = 1, \ldots, m$.

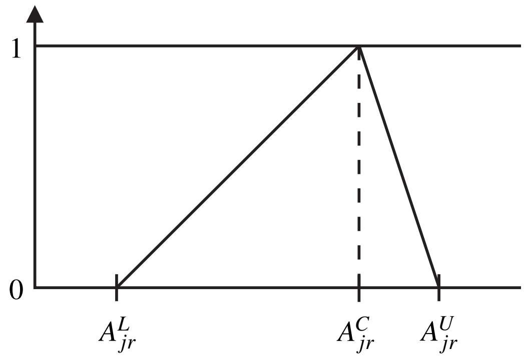

Figure 6: The asymmetric triangular fuzzy coefficient $A_{jr} = (A_{jr}^L, A_{jr}^C, A_{jr}^U)^T$.

When all the fuzzy coefficients are asymmetric triangular, the fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$ are also asymmetric triangular fuzzy numbers (cf. Fig. 7). Therefore, $\mathscr{F}_j$ is given by

$$\mathscr{F}_j\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big), \mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big), \mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big)\big)^T,$$

where

$$\begin{aligned}
\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big) &= Z_{j0}^L + \sum_{r=1}^{n} \delta^L(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho^L(E_s^{(k)})E_s^{(k)},\\
\mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) &= Z_{j0}^C + \sum_{r=1}^{n} A_{jr}^C X_r^{(k)} + \sum_{s=1}^{m} B_{js}^C E_s^{(k)},\\
\mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big) &= Z_{j0}^U + \sum_{r=1}^{n} \delta^U(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho^U(E_s^{(k)})E_s^{(k)}
\end{aligned}$$

with

$$\delta^L(X_r^{(k)}) = \begin{cases} A_{jr}^L & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^U & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^L(E_s^{(k)}) = \begin{cases} B_{js}^L & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^U & \text{, if } E_s^{(k)} < 0 \end{cases},$$

and

$$\delta^U(X_r^{(k)}) = \begin{cases} A_{jr}^U & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^L & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^U(E_s^{(k)}) = \begin{cases} B_{js}^U & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^L & \text{, if } E_s^{(k)} < 0 \end{cases}.$$

Similarly,

$$\mathscr{G}_i\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{G}_i^L\big(X^{(k)},E^{(k)}\big), \mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big), \mathscr{G}_i^U\big(X^{(k)},E^{(k)}\big)\big),$$

where

$$\begin{aligned}
\mathscr{G}_i^L\big(X^{(k)},E^{(k)}\big) &= Z_{i0}'^L + \sum_{r=1}^{n} \delta'^L(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^L(E_s^{(k)})E_s^{(k)},\\
\mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big) &= Z_{i0}'^C + \sum_{r=1}^{n} A_{ir}'^C X_r^{(k)} + \sum_{s=1}^{m} B_{is}'^C E_s^{(k)},\\
\mathscr{G}_i^U\big(X^{(k)},E^{(k)}\big) &= Z_{i0}'^U + \sum_{r=1}^{n} \delta'^U(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^U(E_s^{(k)})E_s^{(k)},
\end{aligned}$$

with

$$\delta'^L(X_r^{(k)}) = \begin{cases} A_{ir}'^L & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^U & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^L(E_s^{(k)}) = \begin{cases} B_{is}'^L & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^U & \text{, if } E_s^{(k)} < 0 \end{cases},$$

and

$$\delta'^U(X_r^{(k)}) = \begin{cases} A_{ir}'^U & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^L & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^U(E_s^{(k)}) = \begin{cases} B_{is}'^U & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^L & \text{, if } E_s^{(k)} < 0 \end{cases}.$$

The α-cut of

$$\mathscr{F}_j\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big),\, \mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big),\, \mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big)\big)^T$$

is the interval

$$\big[\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)\big]_\alpha = \big[\mathscr{F}_{j\alpha}^L\big(X^{(k)},E^{(k)}\big),\, \mathscr{F}_{j\alpha}^U\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\begin{aligned}
\mathscr{F}_{j\alpha}^L\big(X^{(k)},E^{(k)}\big) &= \alpha\cdot\mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) + (1-\alpha)\cdot\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big),\\
\mathscr{F}_{j\alpha}^U\big(X^{(k)},E^{(k)}\big) &= \alpha\cdot\mathscr{F}_j^C\big(X^{(k)},E^{(k)}\big) + (1-\alpha)\cdot\mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big).
\end{aligned}$$

Similarly, the α'-cut of

$$\mathscr{G}_i\big(X^{(k)},E^{(k)}\big) = \big(\mathscr{G}_i^L\big(X^{(k)},E^{(k)}\big),\, \mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big),\, \mathscr{G}_i^U\big(X^{(k)},E^{(k)}\big)\big)^T$$

is the interval

$$\big[\mathscr{G}_i\big(X^{(k)},E^{(k)}\big)\big]_{\alpha'} = \big[\mathscr{G}_{i\alpha'}^L\big(X^{(k)},E^{(k)}\big),\, \mathscr{G}_{i\alpha'}^U\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\begin{aligned}
\mathscr{G}_{i\alpha'}^L\big(X^{(k)},E^{(k)}\big) &= \alpha'\cdot\mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big) + (1-\alpha')\cdot\mathscr{G}_i^L\big(X^{(k)},E^{(k)}\big),\\
\mathscr{G}_{i\alpha'}^U\big(X^{(k)},E^{(k)}\big) &= \alpha'\cdot\mathscr{G}_i^C\big(X^{(k)},E^{(k)}\big) + (1-\alpha')\cdot\mathscr{G}_i^U\big(X^{(k)},E^{(k)}\big).
\end{aligned}$$

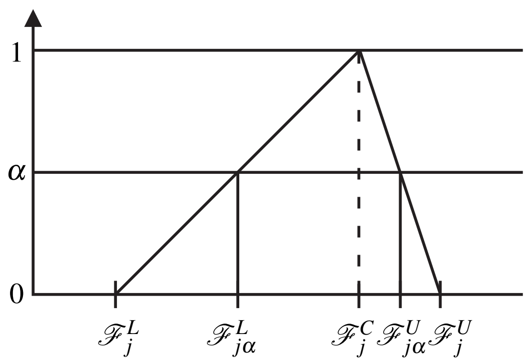

Figure 7: The α-cut of the asymmetric triangular fuzzy model $\mathscr{F}_j$.

In order to determine the centers as well as the upper and lower limits of the asymmetric triangular fuzzy coefficients, we adapt the following *hybrid method of least-squares regression and fuzzy regression* [8]:

Fuzzy-Regression for Target-Environment Data (FR 4)

(1) Apply least squares regression in order to determine the centers $\mathscr{F}_j^C\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$ and $\mathscr{G}_i^C\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$.

(2) Determine the lower limits $\mathscr{F}_j^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$, $\mathscr{G}_i^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$ and the upper limits $\mathscr{F}_j^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$, $\mathscr{G}_i^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$ by solving the following linear programming problem:

$$\begin{aligned}
\text{Minimize}\quad & \sum_{\kappa=0}^{T}\left\{\sum_{j=1}^{n}\left[\mathscr{F}_j^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)-\mathscr{F}_j^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\right]\right. \\
& \qquad\left.+\sum_{i=1}^{m}\left[\mathscr{G}_i^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)-\mathscr{G}_i^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\right]\right\} \\
\text{subject to}\quad & \mathscr{F}_{j\alpha}^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\le\overline{X}_j^{(\kappa+1)}\le\mathscr{F}_{j\alpha}^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right), \\
& \mathscr{G}_{i\alpha'}^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\le\overline{E}_i^{(\kappa+1)}\le\mathscr{G}_{i\alpha'}^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) \\
& (j=1,\dots,n;\ i=1,\dots,m;\ \kappa=0,1,\dots,T), \\
& Z_{j0}^L\le Z_{j0}^C\le Z_{j0}^U,\ Z_{i0}'^L\le Z_{i0}'^C\le Z_{i0}'^U, \\
& A_{jr}^L\le A_{jr}^C\le A_{jr}^U,\ A_{ir}'^L\le A_{ir}'^C\le A_{ir}'^U, \\
& B_{js}^L\le B_{js}^C\le B_{js}^U,\ B_{is}'^L\le B_{is}'^C\le B_{is}'^U \\
& (j,r=1,\dots,n;\ i,s=1,\dots,m;\ \kappa=0,1,\dots,T).
\end{aligned}$$

In Step (1), the centers of the fuzzy coefficients are determined while in Step (2) the lower limits and upper limits of the asymmetric triangular fuzzy coefficients are calculated. The objective function is defined as the total spread of the fuzzy outputs from the linear fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$, i.e., the difference between the upper limit and lower limit of $\mathscr{F}_j$ and $\mathscr{G}_i$, respectively.

Example 4
When we are applying the hybrid method FR4 to the numerical data from Example 1, we obtain a nearly optimal solution. This is because of the linear structure of the initial model presented in Example 1.

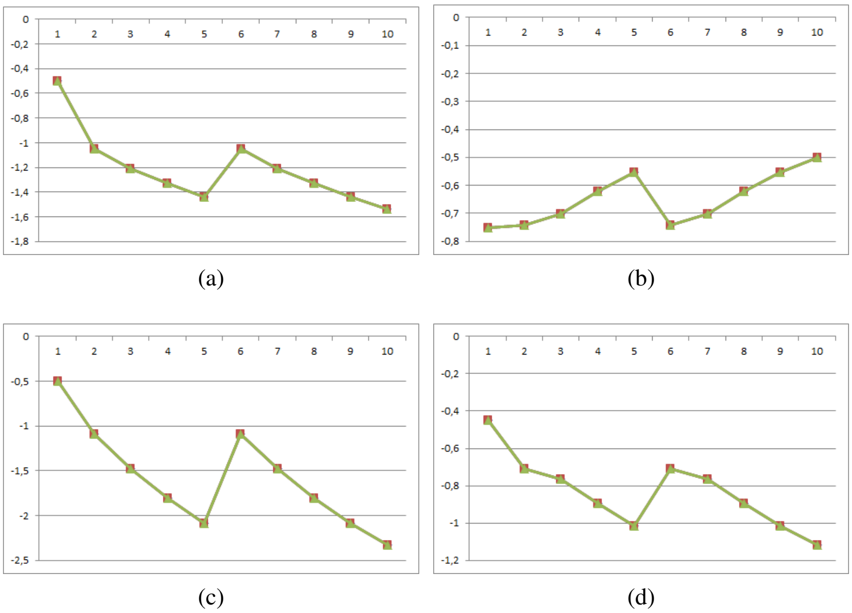

Figure 8: Results of the fuzzy-regression algorithm FR4 for (a) first target, (b) second target, (c) first environmental factor and (d) second environmental factor.

3.4 Fuzzy Regression Based on Trapezoidal Fuzzy Coefficients

Fuzzy regression models with *asymmetric trapezoidal fuzzy coefficients* are proposed in [8] in order to reduce unnecessary fuzziness of the output and to avoid linear programming problems with no feasible solution (cf. Fig. 9). In this section, we will extend our model in this direction and we will use non-fuzzy data sets and asymmetric trapezoidal fuzzy coefficients.

Given the two crisp data sets

$$\left((\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)})^T;\overline{X}_j^{(\kappa+1)}\right),\ \left((\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)})^T;\overline{E}_i^{(\kappa+1)}\right)\quad(\kappa=0,1,\ldots,T),$$

we denote the coefficients as

$$\begin{aligned}
Z_{j0}&=(Z_{j0}^L,Z_{j0}^M,Z_{j0}^N,Z_{j0}^U)^T,\ Z'_{i0}=(Z_{i0}^{\prime L},Z_{i0}^{\prime M},Z_{i0}^{\prime N},Z_{i0}^{\prime U})^T,\\
A_{jr}&=(A_{jr}^L,A_{jr}^M,A_{jr}^N,A_{jr}^U)^T,\ A'_{ir}=(A_{ir}^{\prime L},A_{ir}^{\prime M},A_{ir}^{\prime N},A_{ir}^{\prime U})^T,\\
B_{js}&=(B_{js}^L,B_{js}^M,B_{js}^N,B_{js}^U)^T,\ B'_{is}=(B_{is}^{\prime L},B_{is}^{\prime M},B_{is}^{\prime N},B_{is}^{\prime U})^T,
\end{aligned}$$

where $r=1,\ldots,n$ and $s=1,\ldots,m$.

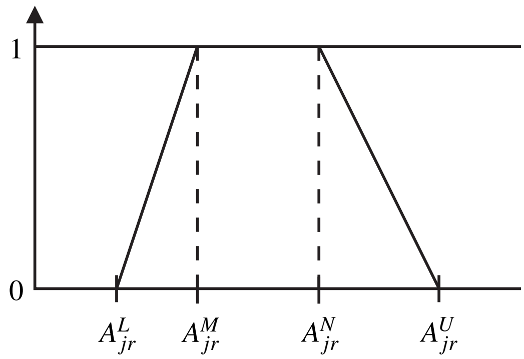

Figure 9: The asymmetric triangular fuzzy coefficient $A_{jr}=(A_{jr}^L,A_{jr}^M,A_{jr}^N,A_{jr}^U)^T$.

The fuzzy models $\mathscr{F}_j$ and $\mathscr{G}_i$ are asymmetric trapezoidal fuzzy numbers. Therefore, $\mathscr{F}_j$ is given by

$$\begin{aligned}
&\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)\\
&=\big(\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big),\mathscr{F}_j^M\big(X^{(k)},E^{(k)}\big),\mathscr{F}_j^N\big(X^{(k)},E^{(k)}\big),\mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big)\big)^T,
\end{aligned}$$

where

$$\begin{aligned}
\mathscr{F}_j^L\big(X^{(k)},E^{(k)}\big)&=Z_{j0}^L+\sum_{r=1}^n\delta^L(X_r^{(k)})X_r^{(k)}+\sum_{s=1}^m\rho^L(E_s^{(k)})E_s^{(k)},\\
\mathscr{F}_j^M\big(X^{(k)},E^{(k)}\big)&=Z_{j0}^M+\sum_{r=1}^n\delta^M(X_r^{(k)})X_r^{(k)}+\sum_{s=1}^m\rho^M(E_s^{(k)})E_s^{(k)},\\
\mathscr{F}_j^N\big(X^{(k)},E^{(k)}\big)&=Z_{j0}^N+\sum_{r=1}^n\delta^N(X_r^{(k)})X_r^{(k)}+\sum_{s=1}^m\rho^N(E_s^{(k)})E_s^{(k)},\\
\mathscr{F}_j^U\big(X^{(k)},E^{(k)}\big)&=Z_{j0}^U+\sum_{r=1}^n\delta^U(X_r^{(k)})X_r^{(k)}+\sum_{s=1}^m\rho^U(E_s^{(k)})E_s^{(k)},
\end{aligned}$$

with

$$\delta^L(X_r^{(k)}) = \begin{cases} A_{jr}^L & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^U & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^L(E_s^{(k)}) = \begin{cases} B_{js}^L & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^U & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta^M(X_r^{(k)}) = \begin{cases} A_{jr}^M & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^N & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^M(E_s^{(k)}) = \begin{cases} B_{js}^M & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^N & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta^N(X_r^{(k)}) = \begin{cases} A_{jr}^N & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^M & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^M(E_s^{(k)}) = \begin{cases} B_{js}^N & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^M & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta^U(X_r^{(k)}) = \begin{cases} A_{jr}^U & \text{, if } X_r^{(k)} \geq 0 \\ A_{jr}^L & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho^U(E_s^{(k)}) = \begin{cases} B_{js}^U & \text{, if } E_s^{(k)} \geq 0 \\ B_{js}^L & \text{, if } E_s^{(k)} < 0 \end{cases}.$$

Similarly,

$$\begin{aligned} &\mathscr{G}_i\big(X^{(k)}, E^{(k)}\big) \\ &= \big(\mathscr{G}_i^L\big(X^{(k)}, E^{(k)}\big), \mathscr{G}_i^M\big(X^{(k)}, E^{(k)}\big), \mathscr{G}_i^N\big(X^{(k)}, E^{(k)}\big), \mathscr{G}_i^U\big(X^{(k)}, E^{(k)}\big)\big)^T, \end{aligned}$$

where

$$\begin{aligned} \mathscr{G}_i^L\big(X^{(k)}, E^{(k)}\big) &= Z_{i0}'^L + \sum_{r=1}^{n} \delta'^L(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^L(E_s^{(k)})E_s^{(k)}, \\ \mathscr{G}_i^M\big(X^{(k)}, E^{(k)}\big) &= Z_{i0}'^M + \sum_{r=1}^{n} \delta'^M(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^M(E_s^{(k)})E_s^{(k)}, \\ \mathscr{G}_i^N\big(X^{(k)}, E^{(k)}\big) &= Z_{i0}'^N + \sum_{r=1}^{n} \delta'^N(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^N(E_s^{(k)})E_s^{(k)}, \\ \mathscr{G}_i^U\big(X^{(k)}, E^{(k)}\big) &= Z_{i0}'^U + \sum_{r=1}^{n} \delta'^U(X_r^{(k)})X_r^{(k)} + \sum_{s=1}^{m} \rho'^U(E_s^{(k)})E_s^{(k)}, \end{aligned}$$

with

$$\delta'^L(X_r^{(k)}) = \begin{cases} A_{ir}'^L & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^U & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^L(E_s^{(k)}) = \begin{cases} B_{is}'^L & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^U & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta'^M(X_r^{(k)}) = \begin{cases} A_{ir}'^M & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^N & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^M(E_s^{(k)}) = \begin{cases} B_{is}'^M & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^N & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta'^N(X_r^{(k)}) = \begin{cases} A_{ir}'^N & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^M & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^N(E_s^{(k)}) = \begin{cases} B_{is}'^N & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^M & \text{, if } E_s^{(k)} < 0 \end{cases},$$

$$\delta'^U(X_r^{(k)}) = \begin{cases} A_{ir}'^U & \text{, if } X_r^{(k)} \geq 0 \\ A_{ir}'^L & \text{, if } X_r^{(k)} < 0 \end{cases}, \qquad \rho'^U(E_s^{(k)}) = \begin{cases} B_{is}'^U & \text{, if } E_s^{(k)} \geq 0 \\ B_{is}'^L & \text{, if } E_s^{(k)} < 0 \end{cases}.$$

The α-cut of $\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)$ is the interval

$$\big[\mathscr{F}_j\big(X^{(k)},E^{(k)}\big)\big]_\alpha = \big[\mathscr{F}^L_{j\alpha}\big(X^{(k)},E^{(k)}\big),\, \mathscr{F}^R_{j\alpha}\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\mathscr{F}^L_{j\alpha}\big(X^{(k)},E^{(k)}\big) = \alpha\cdot\mathscr{F}^M_j\big(X^{(k)},E^{(k)}\big) + (1-\alpha)\cdot\mathscr{F}^L_j\big(X^{(k)},E^{(k)}\big),$$
$$\mathscr{F}^R_{j\alpha}\big(X^{(k)},E^{(k)}\big) = \alpha\cdot\mathscr{F}^N_j\big(X^{(k)},E^{(k)}\big) + (1-\alpha)\cdot\mathscr{F}^U_j\big(X^{(k)},E^{(k)}\big),$$

and the α'-cut of $\mathscr{G}_i\big(X^{(k)},E^{(k)}\big)$ is the interval

$$\big[\mathscr{G}_i\big(X^{(k)},E^{(k)}\big)\big]_{\alpha'} = \big[\mathscr{G}^L_{i\alpha'}\big(X^{(k)},E^{(k)}\big),\, \mathscr{G}^R_{i\alpha'}\big(X^{(k)},E^{(k)}\big)\big],$$

where

$$\mathscr{G}^L_{i\alpha'}\big(X^{(k)},E^{(k)}\big) = \alpha'\cdot\mathscr{G}^M_i\big(X^{(k)},E^{(k)}\big) + (1-\alpha')\cdot\mathscr{G}^L_i\big(X^{(k)},E^{(k)}\big),$$
$$\mathscr{G}^R_{i\alpha'}\big(X^{(k)},E^{(k)}\big) = \alpha'\cdot\mathscr{G}^N_i\big(X^{(k)},E^{(k)}\big) + (1-\alpha')\cdot\mathscr{G}^U_i\big(X^{(k)},E^{(k)}\big).$$

Now, we can state the fuzzy regression model for non-fuzzy target-environment data with asymmetric trapezoidal fuzzy coefficients. In the objective function, we minimize the sum of total spread and inner spread of the fuzzy models which is given by

$$\sum_{j=1}^{n}\left[\big(\mathscr{F}^U_j-\mathscr{F}^L_j\big)+\big(\mathscr{F}^N_j-\mathscr{F}^M_j\big)\right]$$

and

$$\sum_{i=1}^{m}\left[\big(\mathscr{G}^U_i-\mathscr{G}^L_i\big)+\big(\mathscr{G}^N_i-\mathscr{G}^M_i\big)\right],$$

respectively.

Beside the inclusion relations, we impose additional constraints in order to preserve the trapezoidal shape of the fuzzy coefficients:

Fuzzy-Regression for Target-Environment Data (FR 5)

Minimize
$$\sum_{\kappa=0}^{T}\Bigg\{ \sum_{j=1}^{n}\Big[\mathscr{F}_j^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) - \mathscr{F}_j^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) + \mathscr{F}_j^N\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) - \mathscr{F}_j^M\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\Big] + \sum_{i=1}^{m}\Big[\mathscr{G}_i^U\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) - \mathscr{G}_i^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) + \mathscr{G}_i^N\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) - \mathscr{G}_i^M\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)\Big]\Bigg\}$$

subject to
$$\mathscr{F}_{j\alpha}^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) \le \overline{X}_j^{(\kappa+1)} \le \mathscr{F}_{j\alpha}^R\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right),$$
$$\mathscr{G}_{i\alpha'}^L\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right) \le \overline{E}_i^{(\kappa+1)} \le \mathscr{G}_{i\alpha'}^R\left(\overline{\mathbb{X}}^{(\kappa)},\overline{\mathbb{E}}^{(\kappa)}\right)$$
$$(j=1,\ldots,n;\ i=1,\ldots,m;\ \kappa=0,1,\ldots,T),$$

$$Z_{j0}^L \le Z_{j0}^M \le Z_{j0}^N \le Z_{j0}^U,\ Z_{i0}^{\prime L} \le Z_{i0}^{\prime M} \le Z_{i0}^{\prime N} \le Z_{i0}^{\prime U},$$
$$A_{jr}^L \le A_{jr}^M \le A_{jr}^N \le A_{jr}^U,\ A_{ir}^{\prime L} \le A_{ir}^{\prime M} \le A_{ir}^{\prime N} \le A_{ir}^{\prime U},$$
$$B_{js}^L \le B_{js}^M \le B_{js}^N \le B_{js}^U,\ B_{is}^{\prime L} \le B_{is}^{\prime M} \le B_{is}^{\prime N} \le B_{is}^{\prime U}$$
$$(j,r=1,\ldots,n;\ i,s=1,\ldots,m;\ \kappa=0,1,\ldots,T).$$

3.5 Fuzzy Regression Based on Trapezoidal Fuzzy Coefficients with Membership Grades

In this section, we assume that individual membership grades $\alpha_{j\kappa}, \alpha'_{i\kappa} \in (0,1]$ are assigned to the data sets

$$\big((\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)})^T; \overline{X}_j^{(\kappa+1)}\big) \quad \text{and} \quad \big((\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)})^T; \overline{E}_i^{(\kappa+1)}\big) \quad (\kappa = 0, 1, \ldots, T).$$

In this way, the quality of data obtained from a statistical analysis in a preprocessing step can also be reflected in the fuzzy regression with trapezoidal fuzzy coefficients. As in the case of symmetric triangular fuzzy coefficients in Section 3.2, the fuzzy regression model (FR5) with trapezoidal fuzzy coefficients can now be further extended and improved with regard to individual membership grades:

Fuzzy-Regression for Target-Environment Data (FR 6)

Minimize
$$\sum_{\kappa=0}^{T} \Bigg\{ \sum_{j=1}^{n} \alpha_{j\kappa} \cdot \Big[\mathscr{F}_j^U \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) - \mathscr{F}_j^L \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) + \mathscr{F}_j^N \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) - \mathscr{F}_j^M \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \Big]$$
$$+ \sum_{i=1}^{m} \alpha'_{i\kappa} \cdot \Big[\mathscr{G}_i^U \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) - \mathscr{G}_i^L \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) + \mathscr{G}_i^N \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) - \mathscr{G}_i^M \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \Big] \Bigg\}$$

subject to
$$\mathscr{F}_{j\alpha_{j\kappa}}^L \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \le \overline{X}_j^{(\kappa+1)} \le \mathscr{F}_{j\alpha_{j\kappa}}^R \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big),$$
$$\mathscr{G}_{i\alpha'_{i\kappa}}^L \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big) \le \overline{E}_i^{(\kappa+1)} \le \mathscr{G}_{i\alpha'_{i\kappa}}^R \big(\overline{\mathbb{X}}^{(\kappa)}, \overline{\mathbb{E}}^{(\kappa)}\big)$$
$$(j = 1, \ldots, n;\ i = 1, \ldots, m;\ \kappa = 0, 1, \ldots, T),$$

$$Z_{j0}^L \le Z_{j0}^M \le Z_{j0}^N \le Z_{j0}^U,\ Z_{i0}'^L \le Z_{i0}'^M \le Z_{i0}'^N \le Z_{i0}'^U,$$
$$A_{jr}^L \le A_{jr}^M \le A_{jr}^N \le A_{jr}^U,\ A_{ir}'^L \le A_{ir}'^M \le A_{ir}'^N \le A_{ir}'^U,$$
$$B_{js}^L \le B_{js}^M \le B_{js}^N \le B_{js}^U,\ B_{is}'^L \le B_{is}'^M \le B_{is}'^N \le B_{is}'^U$$
$$(j, r = 1, \ldots, n;\ i, s = 1, \ldots, m;\ \kappa = 0, 1, \ldots, T).$$

Finally, Table 2 summarizes the regression models together with the corresponding type of coefficients and model outputs as well as the specific form of the objective function.

Table 2: Fuzzy regression algorithms for target-environment data.

Coefficients	Fuzzy Model Output	Objective Function	Algorithm
symmetric triangular	symmetric triangular	Minimization of total spread of fuzzy coefficients	(FR1)
symmetric triangular	symmetric triangular	Minimization of total spread of fuzzy model output	(FR2)
symmetric triangular	symmetric triangular	Minimization of total spread of fuzzy model output with membership grades	(FR3)
asymmetric triangular	asymmetric triangular	Minimization of total spread of fuzzy model output	(FR4)
asymmetric trapezoidal	asymmetric trapezoidal	Minimization of sum of total spread and inner spread of fuzzy model output	(FR5)
asymmetric trapezoidal	asymmetric trapezoidal	Minimization of sum of total spread and inner spread of fuzzy model output with membership grades	(FR6)

4 Conclusion

The objective of this paper is to introduce fuzzy target-environment networks and fuzzy evolving networks as further approaches for the analysis of two-modal regulatory systems affected by errors and uncertainty. The proposed method is based on a fuzzy model with fuzzy coefficients. Depending on the shape of these uncertain parameters, various possibilistic regression models are obtained. In future works, methods from fuzzy least-squares regression based on a minimization of the total square error of the output can be addressed [5]. In addition, the regression models can be coupled with different types of fuzzy input vectors. Beside the crisp input from measurements also fuzzy input data can be considered in the proposed algorithms which is of particular importance with regard to applications in case of critical operations. For an analysis of nonlinear systems, fuzzy neural networks can be used [8]. A further direction of research could discuss the parameter identification of regulatory systems with interacting groups of variables affected by fuzzy uncertainty. Such an approach could be based on the set-theoretic regression analysis of [14, 15, 16], where functionally related groups of targets and environmental entities under ellipsoidal uncertainty are considered. In future applications, the prediction strategies discussed can be used for a short-time prediction in the framework of multitarget-multisensor tracking in uncertain environments [18, 19]. Critical operations like NBC-tracking in urban scenarios are very challenging and require a rapid decision making based on incomplete or partially observable data. Here, it is of upmost importance to combine the uncertain information in networks with multiple sensor platforms and to predict the future states of the targets.

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