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Black Locust for District Heating: A Fuzzy Inference System

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Abstract In this paper the annual heat's generation at a district heating plant in relation to the cultivating area with black locust and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers. This industrial unit will contribute to the local development as it can provide jobs for a great part of the rural population for the cultivation of black locust. The cultivation of black locust is one of the new promising energy crops for district heating and it constitutes a way out from the problems that the agricultural sector faces nowadays. In this paper an ideal solution was estimated which is formulated as follows "the district heating plant absorbing the black locust's production of a cultivating area of 2,615 acres and having a mean land's yield in the order of 3.2 tons dm/acre/year would produce 4,000 KW of heat annually". 8,369.12 tons dm of black locust biomass should be consumed (burnt) annually for the production of a thermic power of the district heating plant in the order of 4 MW (or 4,000 KW) to meet the needs for space heating and water heating for a community of 400 dwellings. 2,615 acres cultivated with black locust are required for district heating of these dwellings. Such an area of land would offer a complementary occupation to a significant number of young farmers for the cultivation of black locust which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside.

Keywords black locust, district heating plant, fuzzy logic, Mamdani-type FIS

Introduction

The authors believe that the establishment of a district heating industrial unit which will use black locust as a plant raw material will comprise respiration on local level because apart from the heat's production, the cultivation of black locust which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside. In this paper the annual heat's generation at a district heating plant in relation to the cultivating area with black locust and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system).

Black Locust (*Robinia pseudoacacia)*

It is native of south-eastern and central USA between 34-40^{o}N and at altitudes of 1200-3300 m but now it is grown in most temperate and Mediterranean zones of the world especially Hungary which has 350,000 ha [1]. It is a deciduous, leguminous species that is capable of fixing atmospheric nitrogen due to the presence of a bacteria (*Rhizobium*) associated with its shallow root system. It has rapid growth for the first 15-30 years and this ceases after 50 years [2]. It is capable of withstanding dry periods of 2-6 months, however adequate moisture is required if the associated nitrogen-fixing bacteria are to thrive [1]. In its native habitat there is a mean of 1,000 mm/y of rainfall, mainly in summer but it can be grown successfully with as little as 300-400 mm [3]. It tolerates a wide variation in soil types with a pH range 4.2 to 8 [4]. It is also tolerant of temperatures as low as -18 to -20^{o}C [3].

It is established by seedlings and stem cuttings with 10,000-20,000 plants/ha trialled in Greece [2]. Its potential yield in coppice systems has been assessed as 3-14 t dm/ha, with 12 m^3/ha achieved in Greece [2] and 10-14 t dm/ha achieved in Italy [5]. The Black Locust's yield for the infertile rainfed lands ranges from 1.2-2.8 tons dm/acre/year, while for the fertile irrigated lands from 3.2-5.6 tons dm/acre/year [1-2, 5-6]. The wood provides 19.7 Mj/kg dry weight of energy output [7].

Its many benefits include rapid growth first 15-30 years, a height growth peaks in first 5 years, a diameter growth in first 10 years [1], drought tolerance, fixation of N, rapid regeneration, excellent coppicing ability, and a high density wood with high dry matter production. It is also salt and shade tolerant and it is able to grow any poor soil. Black locust can be cut as many as 4 times without a reduction in yield over 10 years [6]. Selection of high production clones being going on for over two centuries central and eastern Europe [1]. It would be an introduced species and therefore would have few pests. There are many uses of its wood, including firewood (Probably the best firewood in the USA [3] and is also planted for shade, shelterbelts, wildlife cover, erosion control, and reclamation. It does have some drawbacks as it spreads by both rudimentary and adventitious root suckers and therefore may become weedy or invasive if not managed properly [4]. Its leaves, roots and bark are poisonous to humans and livestock [4].

District Heating

What is district heating?

District heating systems provide multiple buildings or dwellings with heat and hot water from a central boiler house, or 'energy centre'. The system can provide heating or cooling which is transferred from the energy centre through a network of highly insulated pipes carrying the water to each building. Every building or apartment has a heat exchange unit including a heat meter to monitor how much heat is used.

Depending on the size and density of the network, there are a number of different energy sources that can be used for district heating, including biomass, geothermal heat, energy from waste, solar systems, heat pumps, waste heat from industrial processes, in addition to conventional boilers and cogeneration [8].

Main Components of a District Heating System

Energy is transferred from the energy centre via the district heating pipework, then through two plate heat exchangers housed within the Hydraulic Interface Unit (HIU). The HIU is the equivalent of a domestic combination boiler, providing heat energy to the secondary circuits, domestic hot water & heating within the house.

Advantages of district heating

Compared to owning on-site boiler, conversion to district heating can benefit the user in a number of ways [9-10]:

- Energy Cost - the ability to generate heat at low costs means district heating can contribute to the goal of reducing fuel poverty.
- Reliability - systems are built with stand-by heating capacity to ensure that heat is always available.
- Tenant Comfort - hot water district heating provides even heating that is easily controlled, particularly when compared to older heating systems.
- Reduced Investment - In a new building, the owner avoids the cost of purchasing a boiler and associated facilities such as a flue.
- Energy Efficiency - Conversion to district heating can result in substantial energy savings. The user pays only for the heat that is actually used.
- Domestic hot water can be generated instantaneously through a dedicated heat exchanger, saving the losses incurred with storage and eliminating the time delay in regeneration.

Disadvantages of district heating

- If you have an electric heating system or no central heating you will need to install a wet system (radiator or underfloor piping).
- Upheaval of laying the district heating pipes, although routes to minimise disturbance are available in most cases.
- A reasonable amount of space is required for the central energy centre including fuel storage.
- Having to cross physical barriers, such as railways, major highways and waterways, can make district heating pipe work much more expensive and introduce delays in construction.

District Heating Examples from Europe

Many European countries have long traditions of district heating. Over 100 years ago Denmark commissioned its first CHP plant using household waste to generate electricity with the surplus heat used for district heating. In 2005, Denmark had 430 city- wide (public) district heating systems with 300 CHP units and 130 heat-only boilers. All the heat-only boilers and 15 of the CHPs are fueled by wood or straw. In addition, there are about 480 private (small) CHP and heat-only plants (for greenhouses, schools, etc.). Also, 60% of all houses and residential units in Denmark are supplied with district heating; 25% (or more than 600,000 houses) are heated by biomass- based district heating (Larsen, 2009). For many decades, oil was the primary fuel as district heating spread throughout the country. Renewable energy sources—wood, straw and biogas—became important fuels during the oil crises of the mid- and late-1970s. Climate policies became the key driver for renewables in the 1990s.

Sweden has over 400 wood-fired district heating plants each with a capacity of over 5 MW. Wood fuel in district heating has increased six-fold since 1990 and in 2007 contributed nearly one-half of the feedstock for district heating. In 2007, district heating (as an "energy carrier") contributed about 12% of the total supply in Sweden. At the same time, district heating made up approximately 29% of the energy delivered to the residential and service sectors throughout the country (non-industrial). Renewable energy, as a share of total energy generation in Sweden, was nearly 44% in 2007 [11].

Working with the Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox provides apps to let you perform classical fuzzy system development and pattern recognition. In general, using the Fuzzy Logic Toolbox, you can [12-13]:

- Develop and analyze fuzzy inference systems
- Develop adaptive neurofuzzy inference systems
- Perform fuzzy clustering.

What Are Fuzzy Inference Systems?

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made or patterns discerned. The process of fuzzy inference involves: Membership Functions, Logical Operations and If-Then Rules. Two types of fuzzy inference systems can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined [14-15].

Mamdani-type inference is a type of fuzzy inference in which the fuzzy sets from the consequent of each rule are combined through the aggregation operator and the resulting fuzzy set is defuzzified to yield the output of the system.

Sugeno-type inference is a type of fuzzy inference in which the consequent of each rule is a linear combination of the inputs. The output is a weighted linear combination of the consequents.

Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Mamdani's method was among the first control systems built using fuzzy set theory. It was proposed in 1975 by Ebrahim Mamdani [14] as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Mamdani's effort was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes [16].

Mamdani-type inference expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output membership function rather than a distributed fuzzy set. This type of output is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the more general Mamdani method, which finds the centroid of a two-dimensional function. Rather than integrating across the two-dimensional function to find the centroid, the weighted average of a few data points is used. In general, Sugeno-type systems can be used to model any inference system in which the output membership functions are either linear or constant [17-18].

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems and computer vision. Because of their multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems [19-20].

Methodology

Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools to build a Mamdani-type fuzzy inference system

The Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools were used in this paper to build a Mamdani-type fuzzy inference system (FIS). The following GUI tools were used to build, edit and view the fuzzy inference system:

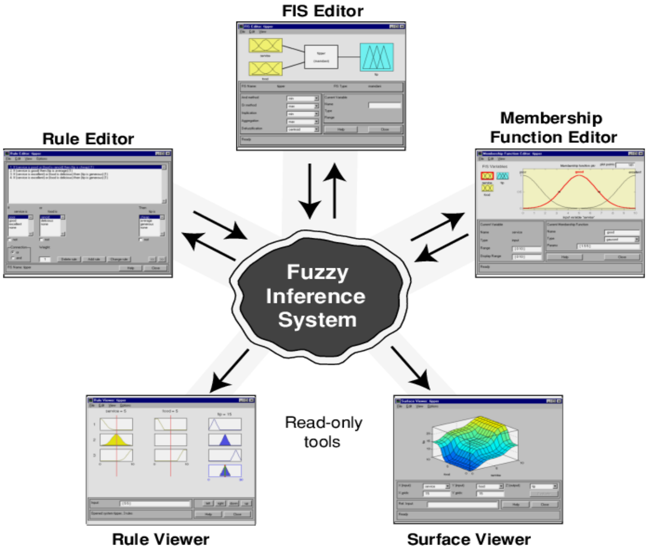

Figure 1: A Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools. The Membership Function Editor (top right), FIS Editor (center), Rule Editor (top left), Rule Viewer (bottom left) and Surface Viewer (bottom right)

Fuzzy Inference System (FIS) Editor to handle the high-level issues for the system—How many input and output variables? What are their names? Fuzzy Logic Toolbox software does not limit the number of inputs. However, the number of inputs may be limited by the available memory of the machine. If the number of inputs is too large or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other tools.

Membership Function Editor to define the shapes of all the membership functions associated with the input and output variables of the FIS.

Rule Editor to edit the list of rules that defines the behavior of the system using full English-like syntax.

Rule Viewer to view the fuzzy inference diagram. Rule Viewer is used as a diagnostic to see, for example, which rules are active or how individual membership function shapes influence the results. Rule Viewer lets you view the detailed behavior of a FIS to help diagnose the behavior of specific rules or study the effect of changing input variables.

Surface Viewer to view the dependency of one of the outputs on any one or two of the inputs. It generates and plots an output surface map for the system. Surface Viewer generates a 3-D surface from two input variables and the output variable of a FIS.

The Problem

Given two sets of numbers, the first one between 0 and 3,400 acres and the second one between 0 and 5.6 tons dm/acre/year that respectively represent the cultivating area with black locust and the land's yield. What should the annual heat's generation be? In this paper the annual heat's generation at a district heating plant in relation to the cultivating area with black locust and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers concerning the range of black locust yield for various land categories (infertile rainfed land, fertile irrigated land).

Results-Discussion

Building of a Mamdani-type Fuzzy Inference System

Fuzzy Approach

The following 3 rules were set:

- If cultivating area with black locust is small and land is infertile rainfed, then the annual heat's generation is low;
- If cultivating area with black locust is satisfactory, then the annual heat's generation is satisfactory;
- If cultivating area with black locust is large or land is fertile irrigated, then the annual heat's generation is high.

The four basic steps for building and simulating of a fuzzy logic system are the following [13, 18, 21]:

a) Defining inputs and outputs;
b) Creating membership functions;
c) Creating rules;
d) Simulating the results of a fuzzy logic system.

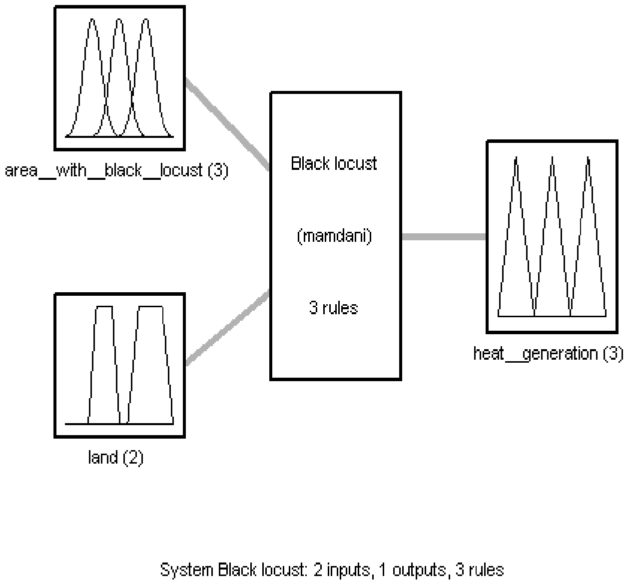

Figure 2: Defining inputs and outputs

1st Step-defining Inputs and Outputs

The Mamdani-type fuzzy inference system was selected in the FIS Editor. This problem has 2 input variables and 1 output variable. The input 1 variable is the "cultivating area with black locust". The input 2 variable is the "land's yield". The output variable is the "annual heat's generation" (Fig. 2).

2nd Step-creating Membership Functions

The membership functions for the 3 variables were defined, namely for the variables: "cultivating area with black locust", "land's yield", "annual heat's generation". The gaussmf was selected as a type of membership function for the input 1 variable "cultivating area with black locust". The number of membership functions is 3 (small, satisfactory, large). The range of "cultivating area with black locust" is between 0 and 3,400 acres (Fig. 3).

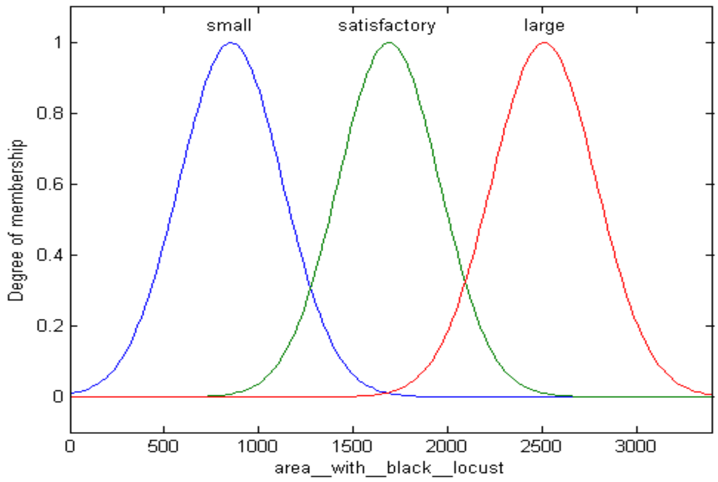

Figure 3: The three membership functions (small, satisfactory, large) for the input 1 variable "cultivating area with black locust"

The trapmf (trapezoid membership function) was selected as a type of membership function for the input 2 variable "land's yield". The number of membership functions is 2 (infertile rainfed, fertile irrigated). The range of "land's yield" is between 0 and 5.6 tons dm/acre/year (Fig. 4).

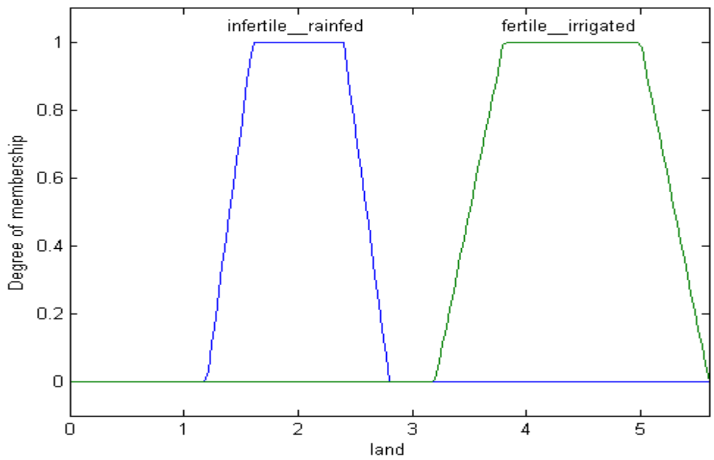

Figure 4: The two membership functions (infertile rainfed, fertile irrigated) for the input 2 variable "land's yield"

The trimf (triangular membership function) was selected as a type of membership function for the output variable "annual heat's generation". The number of membership functions is 3 (low, satisfactory, high). The range of "annual heat generation" is between 0 and 4,810 KW of heat (Fig. 5).

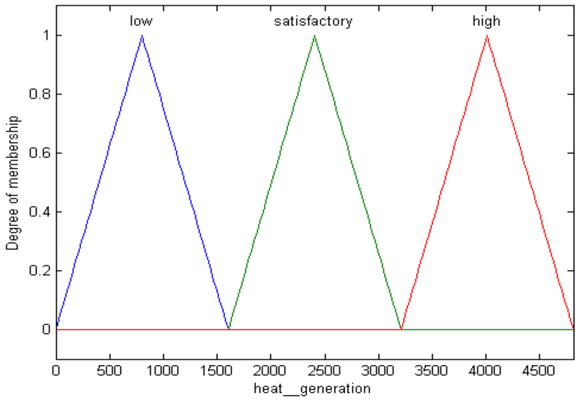

Figure 5: The three membership functions (low, satisfactory, high) for the output variable "annual heat's generation"

3rd Step-creating Rules

Rule statements are constructed automatically in the Rule Editor. The 3 rules of fuzzy approach were added in the Rule Editor (Fig. 6).

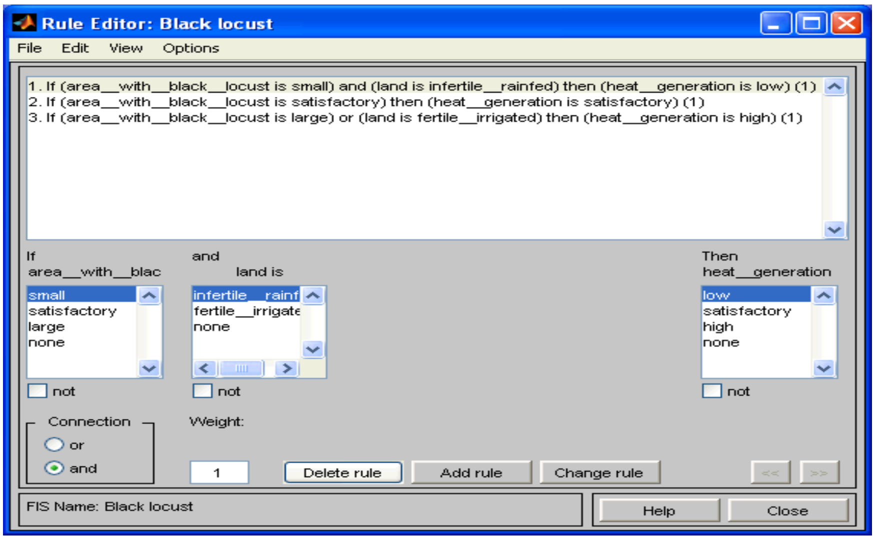

Figure 6: The rule editor: the three rules are appeared in the up part of this window

4th Step-simulating the Results of a Fuzzy Logic System

The results of Rule Viewer (Fig. 7) and Surface Viewer (Fig. 8) of a Mamdani-type fuzzy inference system are simulated and analyzed.

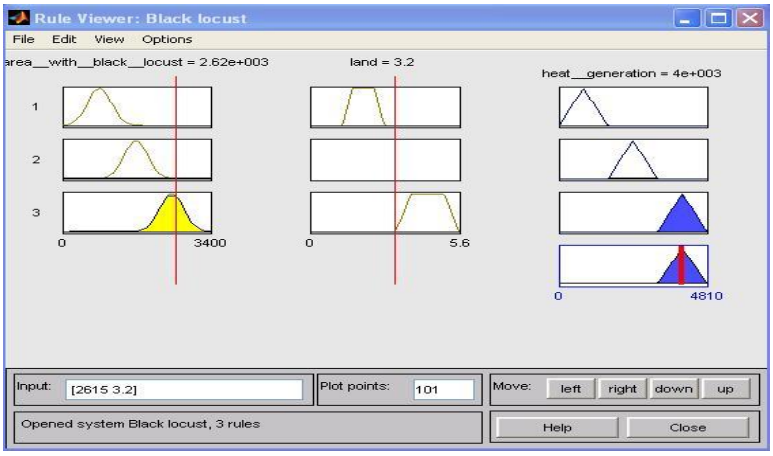

Figure 7: The rule viewer

In the Rule Viewer (Fig. 7), each column shows a set of membership functions for a particular variable. 3 membership functions for "cultivating area with black locust" input 1 variable, 2 membership functions for "land's yield" input 2 variable and 3 membership functions for "annual heat's generation" output variable are presented in Fig. 7.

Each membership function in this set is associated with a particular rule and maps input variable values "cultivating area with black locust" and "land's yield" to rule input values. In other words, the number of rows here is the number of rules that the authors have. The first row corresponds to the first rule, the second row corresponds to the second rule and the third row corresponds to the third rule. The plots in the output column show how the rules are applied to the output variable. The bottom right plot shows how the output of each rule is combined to make an aggregated output and a defuzzified value. The red line provides the defuzzified value for the annual heat's generation. The input value for "cultivating area with black locust" is 2,615 acres and the input value for "land's yield" is 3.2 tons dm/acre/year and they correspond to an output value for "annual heat's generation" equal to 4,000 KW of heat.

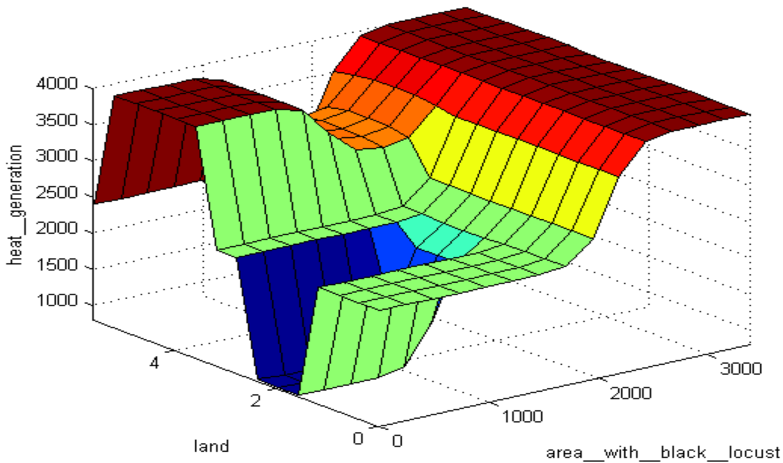

Figure 8: The surface viewer: annual heat's generation as it is affected by the cultivating area with black locust and land's yield

The Surface Viewer (Fig. 8) displays a surface that represents a mapping from the "cultivating area with black locust" and the "land's yield" to the "annual heat's generation". This shows a high value of annual heat's generation for large cultivating area with black locust and fertile irrigated lands, a low value of annual heat's generation for a small cultivating area with black locust and infertile rainfed lands as well as a large flat area in the middle corresponding to a satisfactory (medium) annual heat's generation for satisfactory (medium) cultivating area with black locust.

District heating plant 4MW fuelled with black locust to meet the heating needs of 400 residences

Provided that the district heating plant operates throughout the year and 24 hours / 24 hours, 8,369.12 tons dm of black locust biomass should be consumed (burnt) annually to meet the needs for space heating and water heating for a community of 400 homes (40,000 m^2), where the heating consumers's power is 4 MW (or 4,000 KW). 2,615.35 acres cultivated with black locust are required for district heating of these 400 dwellings. 3.2 tons dm / acre / year were taken as the mean yield of black locust. According to Bain and Overend (2002) 10 KW / residence are required for district heating. The consumption (combustion) of 8,369.12 tons dm of black locust biomass annually is required for the production of a thermic power of the district heating plant in the order of 4 MW (or 4,000 KW) corresponding to a consumption (combustion) of 955.38 Kg dm of black locust biomass per hour.

955.38 Kg / hr x 4,500 Kcal / Kg (calorific value of black locust) = 4,299,226.1 Kcal / hr

4,299,226.1 Kcal / hr corresponding to 100%

X =? Heat which corresponds to 80% (efficiency)

X = 3,439,380.9 Kcal / hr. This is the really heat generated corresponding to the efficiency of 80% and it is equal to 4,000,000 Wh or 4 MW or 4,000 KW.

Exploitation of hot water of the district heating plant during the summer period could become in a drier of agricultural products or more generally in agricultural and forest industries to meet their heating needs during the production process.

Conclusion

Fuzzy inference is a method that interprets the values in the input vector and based on user-defined rules, assigns values to the output vector. Using the editors and viewers in the Fuzzy Logic Toolbox, the rules set were built, the membership functions were defined and the behavior of the fuzzy inference system (FIS) was analyzed.

In this paper the annual heat's generation at a district heating plant in relation to the cultivating area with black locust and to the land's yield was estimated by the building a Mamdani-type fuzzy inference system using the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab (Intelligent system). Data for this study were collected by research papers concerning the range of black locust yield for various land categories (infertile rainfed land, fertile irrigated land). This industrial unit will contribute to the local development as it can provide jobs for a great part of the rural population for the cultivation of black locust. The cultivation of black locust is one of the new promising energy crops for district heating and it constitutes a way out from the problems that the agricultural sector faces nowadays.

The authors built a Mamdani-type fuzzy inference system, namely defined inputs and outputs, created membership functions, created rules and the authors simulated the results of Rule Viewer and Surface Viewer of the fuzzy inference system. The Surface Viewer shows a high value of annual heat's generation for large cultivating area with black locust and fertile irrigated lands and a satisfactory (medium) annual heat's generation for satisfactory (medium) cultivating area with black locust. By the Rule Viewer is shown that the input value for "cultivating area with black locust" is 2,615 acres and the input value for "land's yield" is 3.2 tons dm/acre/year and they correspond to an output value for "annual heat's generation" equal to 4,000 KW of heat. This constitutes the ideal solution in the problem, which was found by using of the Fuzzy Logic Toolbox Graphical User Interface (GUI) Tools of Matlab. In other words, the district heating plant absorbing the black locust's production of a cultivating area of 2,615 acres and having a mean land's yield in the order of 3.2 tons dm/acre/year would produce 4,000 KW of heat annually. 8,369.12 tons dm of black locust biomass should be consumed (burnt) annually for the production of a thermic power of the district heating plant in the order of 4 MW (or 4,000 KW) to meet the needs for space heating and water heating for a community of 400 dwellings. 2,615 acres cultivated with black locust are required for district heating of these dwellings. Such an area of land would offer a collateral occupation to a significant number of young farmers for the cultivation of black locust which will probably be well subsidized, will provide economic motives to the planters, support the agricultural economy and sustain the population in the countryside.

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