NJAS - Wageningen Journal of Life Sciences 70–71 (2014) 61–70

Contents lists available at ScienceDirect

NJAS - Wageningen Journal of Life Sciences

journal homepage: www.elsevier.com/locate/njas

# Greenhouse microclimatic environment controlled by a mobile measuring station

Goran Martinović[a,*], Janos Simon[b]

[a] Faculty of Electrical Engineering, J.J. Strossmayer University of Osijek
[b] Subotica Tech, Department of Informatics

ARTICLE INFO

*Article history:*
Received 16 January 2012
Received in revised form 16 February 2014
Accepted 8 May 2014
Available online 7 June 2014

*Keywords:*
Distant monitoring
FAHP
Greenhouse
Mobile robot
Wireless sensor network

ABSTRACT

This paper investigates a greenhouse microclimatic environment controlled by a mobile measuring station with the aim of improving performance by using wireless sensor networks (WSN) technology. The algorithms for the mobile measuring station that perform navigation tasks are called Bug algorithms. The existing potential field method based algorithms are improved with an RSSI signal propagation model and implemented on a two-wheel driven robot developing system and their performances are measured and analyzed. The implementation part is done on Boe-Bot equipped with SunSPOT enabling the wireless control ability. The control surface is generally made with LabVIEW and a relational database. Control strategy selection system is supported by Fuzzy Analytic Hierarchy Process (FAHP). Navigation of the mobile measuring robot can be done manually, relying on the visual data from the robot's camera, or it can be switched to automatic mode where the developed algorithm does the navigation job. Mobile robot navigation is based on the potential field method considering a wide range of energy-aware parameters.



## 1. Introduction

The aim of this paper is optimization of energy consumption during operation of greenhouses. The proposed system has the option of gathering and monitoring climate parameters related to the microclimatic environment of plants, both inside and outside of the microclimatic environment using wireless sensor networks. The area of research within the controlled microclimate environment is an autonomous mobile measuring station that collects climate data within the environment. For the movement of the robot during measurements in a dynamic environment, an improved method of navigating the mobile monitoring stations was developed based on the potential field method. Mobile robot navigation is based on the potential field method in combination with the received signal strength of the WSN (Wireless Sensor Networks) used as markers to guide the robot. The combination of localization using signal strength of WSN nodes and methods of potential fields leads to the possibility of application of this method in an unknown dynamic environment. From the starting point, the mobile robot should find a path to the target in a dynamic environment, avoiding any obstacles. One of the contributions of research is to improve the performance of mobile robot navigation in an unknown environment. In the interest of optimal energy consumption during operation of greenhouses, a new model of an expert system for managing microclimate multi-criteria decision making based on the application of fuzzy rules is proposed. Six control strategies were developed for managing greenhouse climate and depending on the measured climatic conditions, the choice of an optimal control strategy shall be made by the energy consumption parameter. After a short introduction, Chapter II gives an overview of other researchers' solutions and experimental data. Chapter III describes the environment realized for the purpose of testing the current project. Chapter IV gives an overview of the proposed control strategy selection system based on the Fuzzy Analytic Hierarchy Process (FAHP). Chapter V shows an evaluation of the expert system used in control strategy selection. Chapter VI presents experimental results and analysis of collected data. Chapter VII shows a discussion about the mobile automated greenhouse control system. We concluded Chapter VIII with an overview of the production cycles of the implemented greenhouse environment.

## 2. Related work

The navigation method could manage the robust mechanism guiding the robot along the near-shortest path in static or dynamic

* Corresponding author. Tel.: +38531495401; fax: +38531495402.
*E-mail addresses:* goran.martinovic@etfos.hr (G. Martinović), simon@vts.su.ac.rs (J. Simon).

http://dx.doi.org/10.1016/j.njas.2014.05.007

environments, and no fully informed map is needed. There are few groups doing research work in a greenhouse control system, e.g. [1], [2] and [3]. They use various devices for air temperature, relative humidity and soil temperature measurements with a wireless sensor network. They have also developed a web-based plant monitoring application. A greenhouse grower can read measurements over the Internet, and an alarm will be sent to the owner's mobile phone by SMS or GPRS if some measurement variable changes rapidly. In the test environment, six nodes are deployed into two rows 12.5 m apart from each other. One mesh node works as a repeater and improves the throughput of communication. A bridge node gathers data from other sensor nodes, which transmit temperature and relative humidity measurements in one-minute intervals. Our implementation differs from other developments in the use of a mobile measuring agent, which provides flexibility and robustness for the system. Autonomous robots may be operated by different navigation schemes. The best results were given by a modified implementation of the potential field method. Robot control architecture provides rules, guiding principles and constraints for organizing a robot control system, programs and control algorithms so it can be autonomous and achieve goals [4]. The requirements featuring a WSN are expected to satisfy in effective agricultural monitoring concern both system level issues like unattended operation, maximum network life time, adaptability or even self-reconfigurability of functionalities and protocols and the final user needs e.g. communication reliability and robustness, user friendly, versatile and powerful graphical user interfaces. Serodio [5] developed and tested a similar distributed data acquisition and control system for managing a set of greenhouses. Several communication techniques were used for data communications. At a lower supervision level, inside each greenhouse, a WLAN network with a radio frequency of 433.92 MHz was used to link a sensor network to a local controller. A controller area network (CAN) was provided to link an actuator network to the local controller. Through another RF link (458 MHz), several local controllers were connected to the central computer (PC). High-level data communication was provided through Ethernet to connect the central PC to a remote network. Feng [6] implemented a wireless data acquisition network to collect outdoor and indoor climate data for greenhouses. Several solar-powered data acquisition stations were installed indoor and outdoor to measure and monitor climate data. RF links were established among multiple (up to 32) SPWASs and a base station, which was used to control the SPWASs and to store the data. Liu and Ying [7] reported a greenhouse monitoring and control system using Bluetooth technology. The system collected environment data from a sensor network in a greenhouse and transmitted the data to the central control system. Mizunuma [8] deployed a WLAN in a farm field and greenhouse to monitor plant growth and implemented remote control for the production system. They believed that this type of the remote control strategy could greatly improve productivity and reduce labor requirements.

## 3. Working environment, technology and methods

The applications for WSNs are many and varied. They are used in commercial and industrial applications to monitor data that would be difficult or expensive to monitor by using wired sensors. They could be deployed in wilderness areas, where they would remain for many years (monitoring some environmental variable) without the need to recharge/replace their power supplies. They could form a perimeter about the property and monitor the progression of intruders (passing information from one node to the next). There are many uses of WSNs. Typical applications of WSNs include monitoring, tracking, and controlling. Some of the specific applications are habitat monitoring, object tracking, nuclear reactor controlling, fire detection, traffic monitoring, etc. In a typical application, a WSN is scattered in a region where it is meant to collect data through its sensor node. The WSN-based controller has allowed a considerable decrease in the number of changes in the control action and made a study of the compromise between quantity of transmission and control performance possible. Fig. 1 shows our greenhouse testing environment. The greenhouse protects plants from extreme weather conditions. However, if the period of daylight prevents the photosynthetic activity, the plants do not grow [9]. Horticultural lighting allows the grower to extend the growing season. It enables a year-round production of plants or makes it possible for the grower to start sowing in early spring and continue season until the first frost [10]. Plants need about 10-12 hours of light to improve growth.

Motion control of mobile robots is a very important research field today, because mobile robots are a very interesting subject in both scientific research and practical applications. In this paper, the object of remote control is the Boe-Bot vehicle. The vehicle has two driving wheels and the angular velocities of the two wheels are controlled independently. When the vehicle moves towards the target and the sensors detect an obstacle, an avoiding strategy is necessary, as in [11], [6] and [12]. The host system is connected to the mobile robot with the SunSPOT module. A remote control program has been supported by graphical user interface shown in Fig. 2. As to the greenhouse climate control problem, the system has

**Fig. 1.** Crops in the greenhouse.

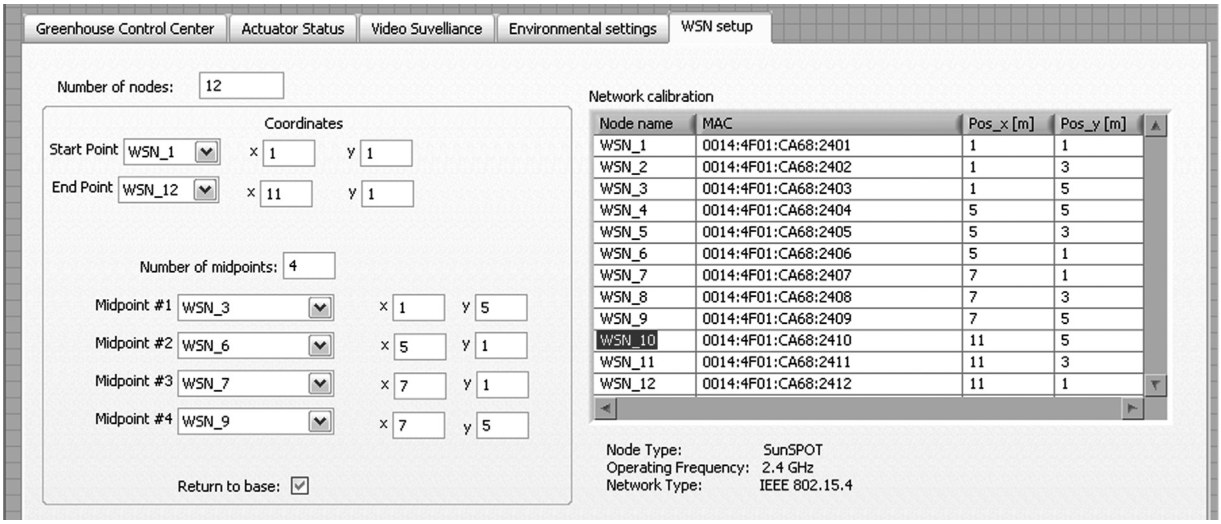


**Fig. 2.** The developed control center window.

provided promising results [13]. This application monitors internal and external parameters of the greenhouse, gives an overview of the actuator's current state, and has a video surveillance option. All the collected data from the mobile measuring station and from the external meteorology station is stored in database. Navigation of the mobile measuring robot can be done manually, relying on the visual data from the robot's camera, or can be switched to automatic mode where the developed algorithm does the navigation job. Deployment of wireless sensors and sensor networks in the greenhouse environment is mostly at the development stage. The aforementioned applications can be classified into five main categories:

- Environmental monitoring,
- Precision agriculture,
- Machine and process control,
- Building and facility automation, and
- Traceability systems.

The implemented wireless sensor network was developed by Sun Microsystems Inc. to provide environmental monitoring in fields. A remote application server can relay data from the sensor network to local users via a WLAN and to remote users via a cellular network and the Internet. We have developed a wireless prototype system to acquire, store, display and transmit real-time environmental data between the greenhouse and remote location. In the control system, a mobile measuring agent navigates between the crops and collects data. Nodes communicate with each other or with a greenhouse server through a WSN. The server collects all the information received from the motes and stores them in a database. Tests demonstrated a great potential to improve efficiency and precision for greenhouse control and data collection. During the past few years, potential field methods (PFM) for obstacle avoidance have gained increased popularity among researchers in the field of robots and mobile robots, as shown in [14], [15] and [16]. The idea of imaginary forces acting on a robot has been suggested by [17]. In these approaches, obstacles exert repulsive forces onto the robot, while the target applies an attractive force to the robot. The sum of all forces, the resultant force, determines the subsequent direction and the speed of travel. According to [18] and [19], one of the reasons for the popularity of this method is its simplicity and efficiency.

The measured values of the greenhouse climate variables are first converted from analog to digital ones and then transmitted to the control system. Because of the high moisture in the greenhouse, the control system is normally located outside. The optimal greenhouse air temperature depends on the intended level of the photosynthetic activity. Each plant species has its own optimal values of air temperature and active radiation of light, which enable the maximum photosynthetic activity. Soil temperature also plays an important role. Conduction heat transfers directly to the soil structure and through convection between the plant roots and water flow around them [20]. The main concern in humidity and temperature control is to provide the best conductivity to active movement of water and nutrients through the plant. Humidity control is also an important tool to prevent the spread of plant diseases in greenhouses. Fig. 3 shows a data fusion structure in greenhouse environment with implemented sensors and actuators responsible for climate conditioning.

The range sensors assist only for wall following and wall detecting purposes. For a greenhouse environment, the mobile measuring agent is equipped with Agricultural Sensor and Gas Sensor boards, and they can be used together to measure and control air humidity, $CO_2$ level and air temperature. Using a PAR (Photosynthetically Active Radiation), the sensor checks the conditions for photosynthesis [21]. Fig. 4 shows the complete control system of the greenhouse, similarly to [22]. The actuator part, like heaters, foggers, coolers of the system, is controlled by a LabVIEW application. All necessary actuators are used to create a relatively constant environmental condition inside the greenhouse. If the temperature rises, the control system enables cooling fans and foggers until we get an acceptable temperature. If the temperature falls below normal, oil heaters activate. The mobile measuring agent does not need to monitor values continuously and it can spend long periods in a power saving mode. In our case, the measuring tour across the greenhouse is made once per hour. The collected data is transmitted to a relational database for further statistical analysis. Using sensor data automatically adjusts the control system to match local conditions in the greenhouse. Avoiding over-watering also helps prevent certain crop diseases including rot, fungi and bacteria, which thrive in wet conditions.

## 4. Fuzzy AHP approach to choose a control strategy

As with most issues related to decision making, selection of the control strategy becomes complicated in a real environment. There is a high probability that the human factor is wrong in making decisions or predictions for quantitative problems. In many

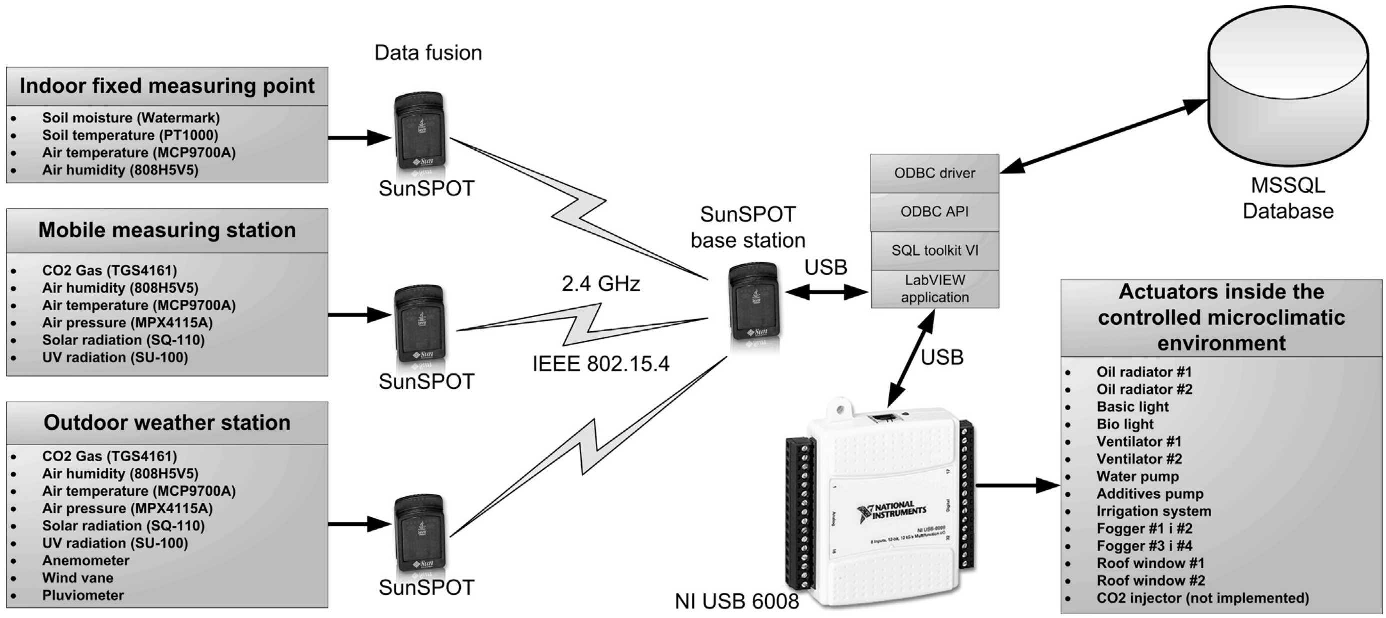


**Fig. 3.** Data fusion structure in the greenhouse environment.

cases, it tends to express the current state of the system with verbal expressions. A fuzzy linguistic model allows mapping of a verbal expression to a numeric value. A multi-criteria decision-making method based on fuzzy relations is used for quantitative determination of the importance of each criterion with some degree of inaccuracy. In this case, the FAHP (Fuzzy Analytic Hierarchy Process) multi-criteria analysis is proposed as a tool for the implementation of a multi-criteria scheme. AHP is a method for decision-making, which is suitable for solving complex unstructured and multi-attribute problems developed by T.L. Saaty [23]. The most creative part in making decisions that greatly affect the outcome of the decision is problem modeling. Identification of the hierarchy of decisions is a key factor in the application of the AHP method. AHP is the basis for the formalization of complex problems using the hierarchical structure of the application by comparing pairs of attributes. This method is widely applied in industrial applications and other areas. Conventional AHP is not able to reflect the human thinking style. For this reason, FAHP is developed to solve the hierarchical fuzzy problems. In the FAHP method, all calculations are performed with fuzzy numbers, as proposed in [24]. In this part, the FAHP method is considered for the selection of control strategies in managing microclimate conditions applying the multi-criteria decision making process. For the purpose of defining a fuzzy set, let $X$ be the defined area, $\tilde{A}$ a fuzzy subset of $X$ such that it applies to all $x \in X$. Let there be a number $\mu_{\tilde{A}}(x \in [0,1])$ assigned to represent the membership of $x$ to $\tilde{A}$ and let $\mu_{\tilde{A}}(x)$ be called the membership function of $\tilde{A}$. A fuzzy number $\tilde{A}$ is a normal and convex fuzzy subset of $X$. According to [25], a convex set implies (1):

$$\begin{aligned} &\forall x_1 \in X, x_2 \in X, \quad \forall \alpha \in [0,1] \\ &\mu_{\tilde{A}}(ax_1 + (1-a)x_2 \geq \min \mu_{\tilde{A}}(x_1), \mu_{\tilde{A}}(x_2)) \end{aligned} \tag{1}$$

A triangular fuzzy number $\tilde{A}$ can be defined by a triplet $(a, b, c)$. The membership function can be defined as in [25]:

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-a}{b-a}, & a \leq x \leq b, \\ \dfrac{c-x}{c-b}, & b \leq x \leq c, \\ 0 & . \end{cases} \tag{2}$$

Well known addition, multiplication, subtraction and division of triangular fuzzy numbers are described in [25] and two of these operations used in this paper can be expressed as follows:

Addition of fuzzy numbers $\oplus$:

$$(a_1, b_1, c_1) \oplus (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \tag{3}$$

Multiplication of fuzzy numbers $\otimes$:

$$(a_1, b_1, c_1) \otimes (a_2, b_2, c_2) = (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2) \tag{4}$$

The FAHP method is a systematic approach to the choice of alternatives and justification of the problem using the concepts of fuzzy sets and analysis of hierarchical structures. The decision maker can specify the settings in the form of the natural language or a numeric value on the importance of each attribute. The system combines these settings with existing data using the FAHP method. In the FAHP method, pairwise comparisons in the matrix are fuzzy numbers and fuzzy arithmetic operators. The procedure calculates the sequence of weight vectors that will be used for the selection of the main attributes. In some cases, the decision maker can determine the importance in a standard form with pairwise comparisons defined by T.L. Saaty [23] in the form of nine points on the scale of importance between the two elements. Triangular fuzzy numbers were introduced in the conventional AHP in order to improve the level of judgment of decision makers. The central value of the fuzzy number is the corresponding actual value. Expanding the number is an estimate of the actual number. If the decision maker is unable to specify their preferences according to numerical values, it is also possible to specify the setting in the form of natural language expressions of the importance of each performance attributes. The decision maker also uses the fuzzy method for the construction of the lookup table and the appropriate value of fuzzy numbers similar as in [24]. In the FAHP method, using fuzzy arithmetic and aggregation operators, the procedure calculates the sequence of weight vectors that are used to determine the importance of each attribute. There are many variations FAHP methods and improvements proposed by several researchers. In the next few steps, the method analysis will be given and then the method will be applied to the problem of selecting the optimal control strategy.

Step 1: In the first step, the FAHP method develops the hierarchical structure of the problem similar to [23]. After that, the decision

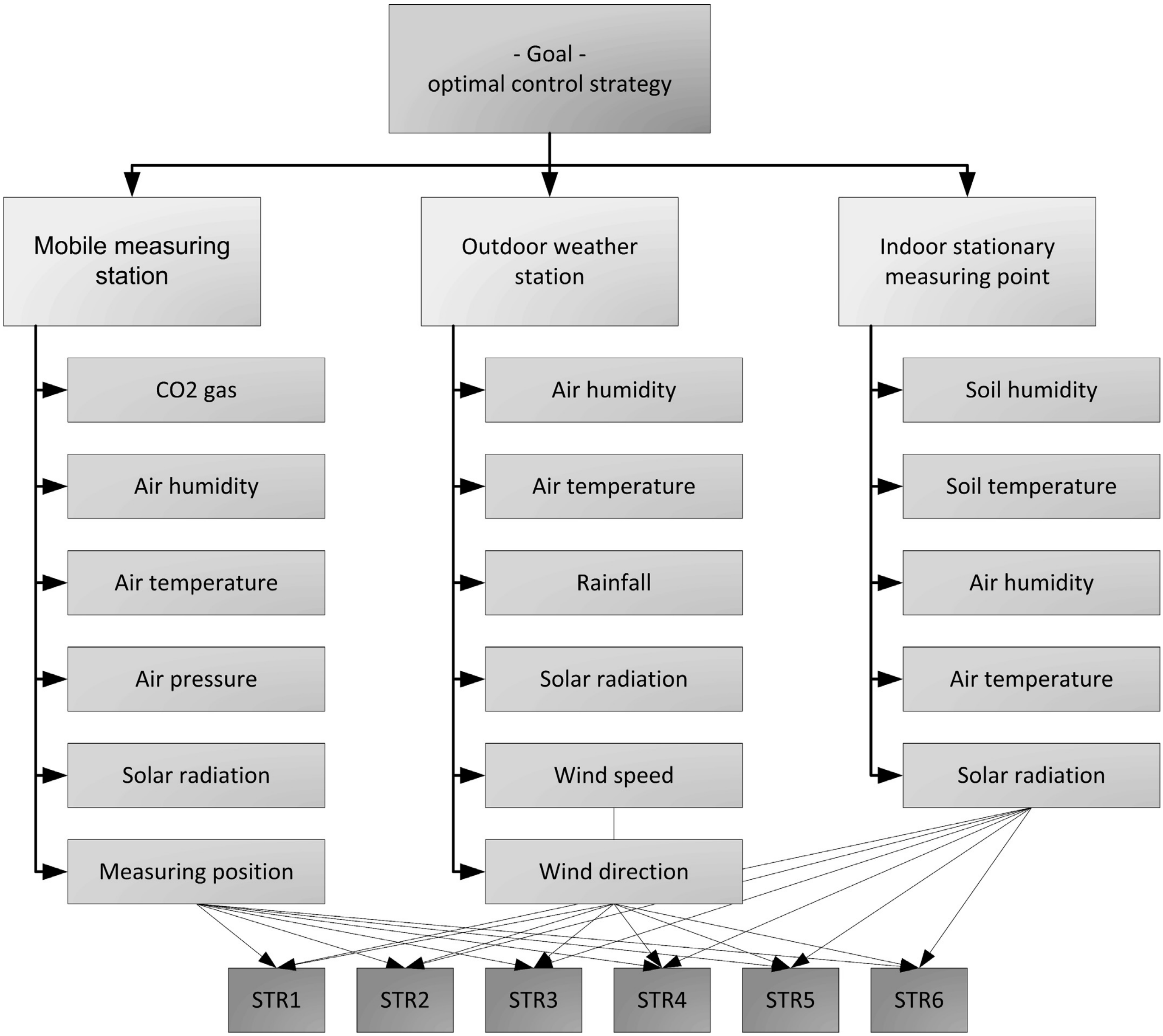


**Fig. 4.** A hierarchy for the selection of the control strategy.

maker must determine relative weighting factors for each criterion. With the AHP method, weighting factors are determined by pairwise comparison of each criterion. To determine the relative weight, the decision maker is asked to make pair-wise comparison by using a scale from $\tilde{1} - \tilde{9}$. Data from pairwise comparison is organized in the form of triangular fuzzy numbers.

Step 2: If the decision maker cannot use preferences forms of triangular fuzzy numbers, there is a possibility of using linguistic terms by applying the lookup table from which the corresponding values can be readily extracted for fuzzy numbers.

Step 3: After setting up the hierarchy and pairwise comparison of the criteria and alternatives, it is necessary to calculate the global value of priority of alternatives as presented in [23].

In order to determine the optimal strategy for managing microclimate conditions, a hierarchical model is devised, as shown in Fig. 4. In this case, the FAHP method is used for determining the optimal control strategy based on the measured data.

The first level is the goal itself. In this case, the goal is to determine the optimal control strategy. The goal is divided into the following three main criteria: A - mobile measuring station, B - outdoor weather station, and C - indoor stationary measuring point. The third level includes system parameters. Improved algorithmic steps of the proposed approach from [25] are shown in Fig. 5.

Category one – The mobile measuring station: General terms and conditions inside the microclimate environment are measured by using a mobile measuring station equipped with the necessary sensors. Data collected from the environment are forwarded to the central database with the exact location and time of measurement. Influencing factors are divided into six sub-criteria: A1 - $CO_2$ gas concentration, A2 – Air humidity, A3 - Air temperature, A4 - Atmospheric pressure, A5 - Solar radiation, A6 - Position of the measurement.

Category two – Outdoor weather station: To control microclimate conditions, it is necessary to monitor external climate factors as well. Data collected from the outside weather stations are also placed in the database. Taking into account external factors, the second criterion is divided into six sub-criteria: B1 - Humidity, B2

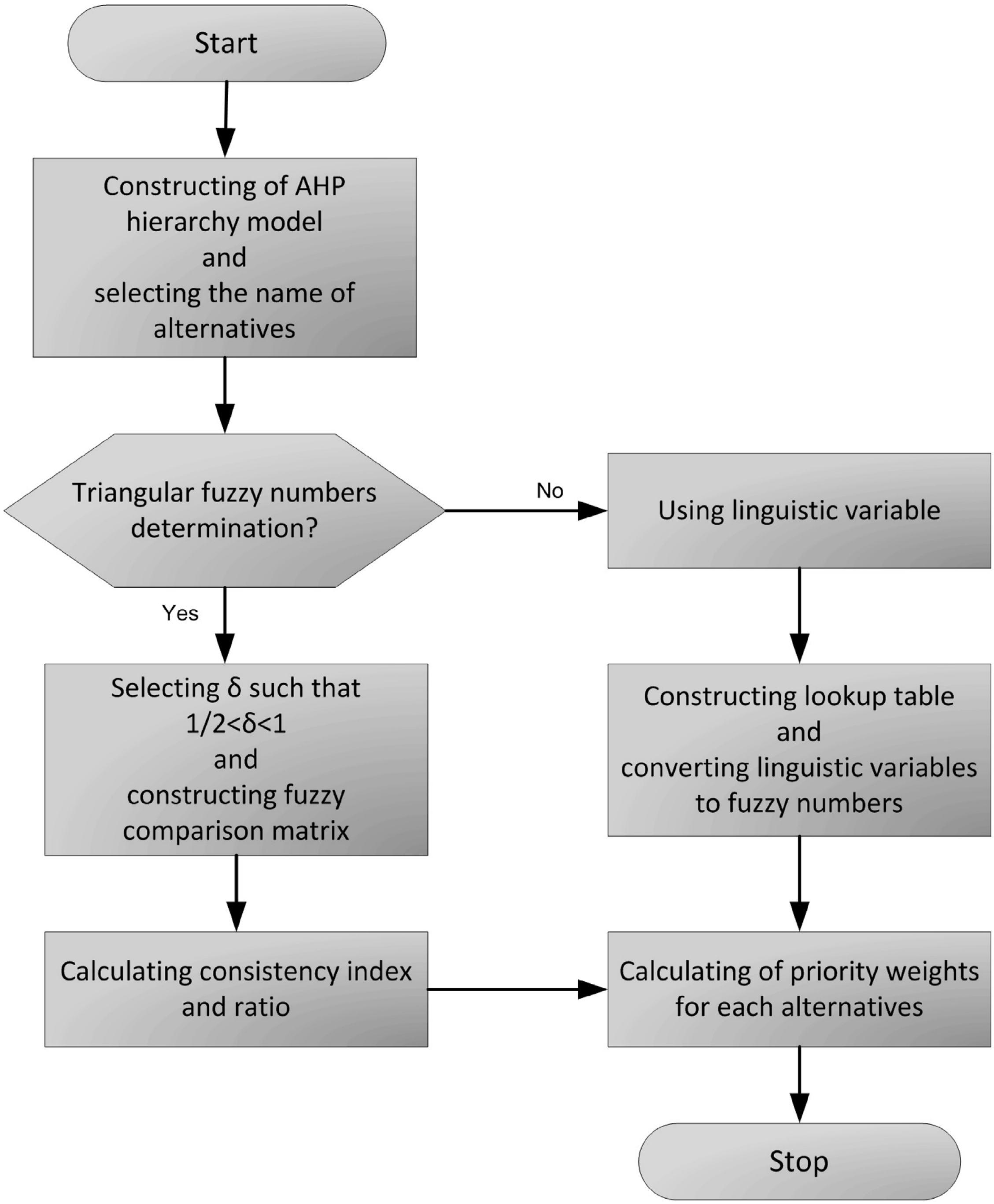


**Fig. 5.** Improved algorithmic steps of the FAHP approach.

- Air temperature, B3 - The amount of rainfall, B4 - Solar radiation, B5 - Wind Speed, B6 - Wind direction.

Category three – Indoor stationary measuring point: The indoor stationary measuring point is introduced for the purpose of improving control performance. Besides standard internal factors such as temperature, relative humidity, lighting conditions, etc., we measure the soil temperature and soil moisture. The third criterion is divided into five sub-criteria: C1 - Soil moisture, C2 - Soil temperature, C3 - Air temperature, C4 - Air humidity, C5 - Solar radiation.

Finally, the fourth and final level contains alternatives. Six control strategies were developed: STR1 – Day_High_Performance, STR2 – Day_Normal, STR3 – Day_Economic, STR4 – Night_High_Performance, STR5 – Night_Normal, STR6 – Night_Economic.

The selection of the optimal control strategy is based upon input factors. Procedures of FAHP calculations are given in the following way, similar as in [23]:

Procedure 1 – In order to determine the optimal control strategy, a hierarchical structure is created as shown in Fig. 4. Taking into consideration the requirements of the goal, the decision maker plays a key role in the evaluation, evaluating the results of pairwise comparison of the first level of the hierarchy. By applying triangular fuzzy numbers, using pairwise comparison, the fuzzy judgment matrix is constructed as $\tilde{A}_{(i,j)}$, where $a_{ij}^{-\alpha} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-3}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$ if $i$ is not equal to $j$, similar to [23]. Membership functions are performed by using an $\alpha$ cut. The $\alpha$ cut plays the role of unifying reliability properties of experts and decision makers during the judgment process. This will give a set of values

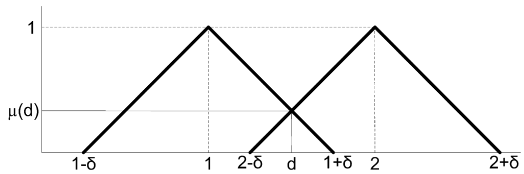


**Fig. 6.** Construction of the fuzzy judgment matrix.

in the interval of fuzzy numbers. The lower limit and upper limit of fuzzy numbers with respect to the $\alpha$ cut are defined by equation described in [23]. $\tilde{a}_{ij} = [a_{ij}, b_{ij}, c_{ij}]$ is one of the elements of $\tilde{A}$ with a closed interval whose mid value is $b_{ij}$. Then $b_{ij}$ is just one of the integers from one to nine, which are used in the method of AHP in [26] and [27].

According to [25], when $\delta$ is selected to be less than 1/2, $b_{ij}$ is selected as the consecutive two-level scale midpoint, and $d$ is the crossover point of two triangles (Fig. 6). If $\mu(d)$ is zero, there is no impact on the entire distinct cognitive-fuzzy conversion. If $\delta$ has a value greater than one, the level of fuzziness increases, but the degree of confidence decreases. It is proposed to select a value for $\delta$ between 1/2 and 1, as shown in Fig. 6.

After pairwise comparison of all elements, matrix $\tilde{A}$ is converted into fuzzy triangular numbers, and the geometric mean method is applied to calculate the priorities of these triangular fuzzy numbers [23], as in (5) and (6).

$$\tilde{k}_i = \left(\prod \tilde{a}_{ij}\right)^{1/n} \quad i = 1, \ldots, n \tag{5}$$

Value of $\tilde{a}_{ij}$ can be defined as $\tilde{a}_{ir1j}, \tilde{a}_{ir2j}, \tilde{a}_{ir3j}$:

$$\left.\begin{aligned} k_{ir1} &= \left(\prod a_{ir1,j}\right)^{1/n} \\ k_{ir2} &= \left(\prod a_{ir2,j}\right)^{1/n} \\ k_{ir3} &= \left(\prod a_{ir3,j}\right)^{1/n} \end{aligned}\right\} \quad j = 1, \ldots, n \tag{6}$$

According to [23], for each of the alternatives or criteria, weights can be computed as follows in (7):

$$\left.\begin{aligned} q_{ir1} &= \frac{k_{ir1}}{\sum_{i=1}^{n} k_{ir3}} \\ q_{ir2} &= \frac{k_{ir2}}{\sum_{i=1}^{n} k_{ir2}} \\ q_{ir3} &= \frac{k_{ir3}}{\sum_{i=1}^{n} k_{ir1}} \end{aligned}\right\} \quad i = 1, \ldots, n \tag{7}$$

Fig. 7 shows usual and known conversion procedure of a linguistic variable into fuzzy numbers, as described in [25].

After that, the weight of criteria $i$ can be written as $\tilde{q}_i = (q_{i,r1}, q_{i,r2}, q_{i,r3})$. The given weights are in the form of triangular fuzzy numbers. The defuzzification process [13] is done according to (8):

$$q_i = \frac{\tilde{q}_i}{3} \tag{8}$$

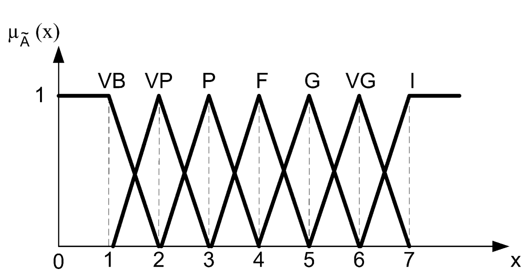


**Fig. 7.** Membership functions of linguistic values for criteria rating.

**Table 1**
Definition of fuzzy members.

| Fuzzy language | Fuzzy values | Meaning |
|---|---|---|
| **VB** | (1,1,2) | Very Bad |
| **VP** | (1,2,3) | Very Poor |
| **P** | (2,3,4) | Poor |
| **F** | (3,4,5) | Fair |
| **G** | (4,5,6) | Good |
| **VG** | (5,6,7) | Very Good |
| **I** | (6,7,7) | Ideal |

**Table 2**
Values of the first hierarchy level.

| | A | B | C |
|---|---|---|---|
| **A** | 1 | 2 | 5 |
| **B** | 1/2 | 1 | 3 |
| **C** | 1/5 | 1/3 | 1 |

**Table 3**
The evaluation matrix of the A criteria.

| | A1 | A2 | A3 | A4 | A5 | A6 |
|---|---|---|---|---|---|---|
| **A1** | 1 | 1/3 | 2 | 1/3 | 1/5 | 1 |
| **A2** | 3 | 1 | 2 | 2 | 1/2 | 5 |
| **A3** | 1/2 | 1/2 | 1 | 1/2 | 1/3 | 1 |
| **A4** | 3 | 1/2 | 2 | 1 | 1/2 | 3 |
| **A5** | 5 | 2 | 3 | 2 | 1 | 5 |
| **A6** | 1 | 1/5 | 1 | 1/3 | 1/5 | 1 |

**Table 4**
The evaluation matrix of the B criteria.

| | B1 | B2 | B3 | B4 | B5 | B6 |
|---|---|---|---|---|---|---|
| **B1** | 1 | 3 | 1 | 1/4 | 1/3 | 2 |
| **B2** | 1/3 | 1 | 1 | 1/3 | 1/2 | 1 |
| **B3** | 1 | 1 | 1 | 1/2 | 1 | 2 |
| **B4** | 4 | 3 | 2 | 1 | 3 | 3 |
| **B5** | 3 | 2 | 1 | 1/3 | 1 | 1 |
| **B6** | 1/2 | 1 | 1/2 | 1/3 | 1 | 1 |

Procedure 2 – If the decision maker is unable to determine the importance or the priority of criteria, it is possible to use linguistic variables to estimate the importance of criteria with respect to the goal, and linguistic variables to estimate the importance of alternatives with respect to each criterion [13]. As described in [25], the linguistic variable can be easily converted into fuzzy numbers according to standard procedure by using Fig. 7 and Table 1.

Procedure 3 – The degree of importance of each objective can be incorporated into the formulation by applying fuzzy priorities and evaluating alternatives. A weighted priority of each alternative can be obtained by multiplying the evaluation matrix by vector weights and by summing of all attributes. Tables 2–5 show the evaluation matrix relevant to individual criteria in greenhouse environment. To determine the relative weight, the decision maker is asked to make pairwise comparison by using a scale from $\tilde{1} - \tilde{9}$ similar to

**Table 5**
The evaluation matrix of the C criteria.

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| **C1** | 1 | 5 | 7 | 2 | 3 |
| **C2** | 1/5 | 1 | 1 | 1/3 | 1/3 |
| **C3** | 1/7 | 1 | 1 | 1/5 | 1/5 |
| **C4** | 1/2 | 3 | 5 | 1 | 1 |
| **C5** | 1/3 | 3 | 5 | 1 | 1 |

**Table 6**
Linguistic evaluations of alternatives according to criteria.

| Alternatives | Criteria | | | | | |
|---|---|---|---|---|---|---|
| | A1/B1/C1 | A2/B2/C2 | A3/B3/C3 | A4/B4/C4 | A5/B5/C5 | A6/B6 |
| **STR1** | G/G/F | F/G/G | VG/F/G | G/F/VG | G/VG/VG | G/VP |
| **STR2** | VG/F/G | F/G/G | F/G/I | VP/G/G | F/G/G | VG/F |
| **STR3** | VP/VG/F | VG/F/F | VG/VP/G | G/G/F | VG/VG/F | VG/G |
| **STR4** | F/G/G | F/G/VG | VP/VG/F | VG/VG/VP | G/VG/F | G/F |
| **STR5** | VG/G/VG | I/F/G | G/F/G | G/F/VG | G/G/F | VP/F |
| **STR6** | VP/G/VG | F/F/F | VG/G/G | I/VP/VP | VG/VG/G | VG/G |

**Table 7**
Comparison of two weighted methods with different δ values.

| δ = 0.6 | | | | δ = 0.7 | | | | δ = 0.8 | | | | δ = 0.9 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FAHP | | Yager | | FAHP | | Yager | | FAHP | | Yager | | FAHP | | Yager | |
| Rank | Score | Rank | Score | Rank | Score | Rank | Score | Rank | Score | Rank | Score | Rank | Score | Rank | Score |
| STR3 | 6.24 | STR3 | 0.99 | STR3 | 6.62 | STR3 | 0.98 | STR3 | 7.07 | STR3 | 0.98 | STR3 | 7.61 | STR3 | 0.98 |
| STR5 | 6.08 | STR6 | 0.98 | STR5 | 6.44 | STR6 | 0.96 | STR5 | 6.86 | STR6 | 0.96 | STR5 | 7.38 | STR6 | 0.96 |
| STR4 | 5.95 | STR5 | 0.95 | STR4 | 6.31 | STR5 | 0.95 | STR4 | 6.74 | STR5 | 0.95 | STR4 | 7.24 | STR5 | 0.95 |
| STR6 | 5.91 | STR4 | 0.95 | STR6 | 6.25 | STR4 | 0.95 | STR6 | 6.67 | STR4 | 0.95 | STR6 | 7. 6 | STR4 | 0.95 |
| STR1 | 5.78 | STR1 | 0.93 | STR1 | 6. 32 | STR1 | 0.94 | STR1 | 6.55 | STR1 | 0.95 | STR1 | 7.04 | STR1 | 0.95 |
| STR2 | 5.35 | STR2 | 0.89 | STR2 | 5.66 | STR2 | 0.89 | STR2 | 6.04 | STR2 | 0.89 | STR2 | 6.50 | STR2 | 0.89 |

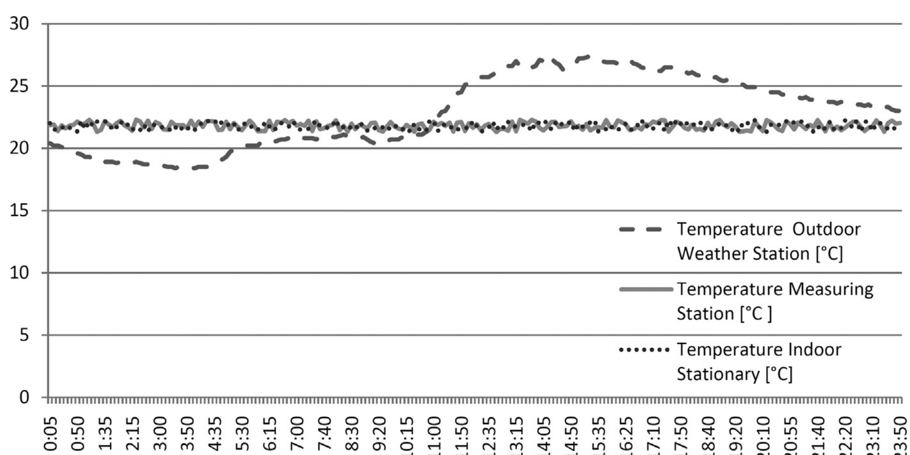


**Fig. 8.** Measured temperature.

[23]. Data from pairwise comparison is organized in the form of triangular fuzzy numbers.

$$f(a_j, q_i) = \sum \tilde{q}_j \otimes \tilde{a}_j \quad (9)$$

One of the six alternative control strategies is chosen as the optimal strategy for the given conditions. Table 6 shows linguistic evaluations linked to specific criteria. After obtaining triangular fuzzy numbers, their priority (geometric mean method) is calculated by using (5) and (6).

For each criterion or alternative, the weighting factor is calculated by using (6). After defuzzification of fuzzy weights, the new value of weighting factors can be obtained by using (8).

## 5. Evaluation of the expert system

In order to show the applicability of the proposed expert system, the proposed method is compared with Yager's method under various δ cuts. The values of δ cut are 0.6, 0.7, 0.8 and 0.9 for the evaluation of six alternatives in FAHP and Yager's method and the results are shown in Table 7.

Both methods are implemented in the MATLAB programming environment to provide experimental values. Comparing models with both methods under various δ cut levels can be considered as a decision support model since it guides decision makers to select the best alternative. In the case of the analysis in Table 7, we can establish that under given conditions STR3_Day_Economic is offered as the best choice for all δ sections in FAHP and Yager's approach. Both methods are insensitive to the values of δ because the evaluation results do not change in the case of various δ sections. This fact proves reliability and consistency of both methods. In the case of ranking all available alternatives, there are certain differences in two methods. The advantage of the FAHP approach is that it is more natural and the input parameters for the application of the fuzzy linguistic variable are defined more precisely, and therefore the decision of an expert system itself is more reliable.

## 6. Experimental results and analysis

Experimental measurements are done inside the greenhouse. The basic surface of the microclimate environment is almost 16 $m^2$, the model is built for experimental purposes in the backyard of Subotica-Tech. 25 containers are located inside the controlled microclimatic environment, and in each of them there is one plant. The possibility of implementing a fuzzy controller used as a substitute for the conventional control system in terms of maintaining the desired temperature in the microclimatic environment that is 21 °C

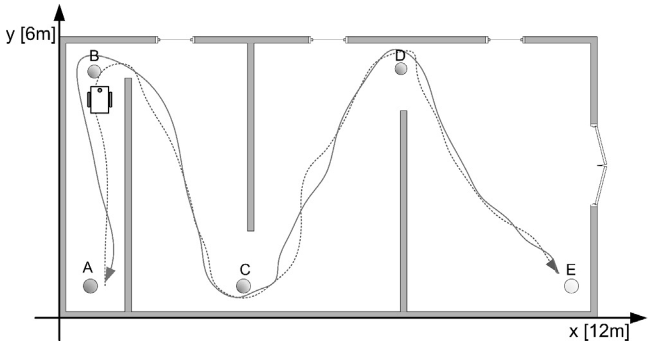


**Fig. 9.** Simulated map.

entails precise control. Fig. 8 shows the graph of measured external temperature, internal temperature and from the temperature sensor on the mobile measuring agent in a period 0-24 h. We are able to manage internal conditions inside the greenhouse at a relatively constant value, which is realized by using good and robust control techniques.

This research considers the information-aware operation of the nodes and of the network as a whole. This involves consideration of the 'information' contained in each packet by quantifying the usefulness of data to the control system [28]. The mobile robot has one WSN node onboard and it communicates with other nodes in the WSN network. This means that we have a WSN grid with a known node position and a mobile node on the robot. The mobile node is localizable by using the RSSI parameter of the three closest nodes. For the localization of mobile measurement stations a minimum of three WSN nodes is required that are in the range of the measuring station. Since the positions of fixed nodes are known, simply by measuring the RSSI signal from the three nearest node, we can determine the exact position of the measuring station. In [11], detailed navigation algorithm for mobile measuring station is presented. Fig. 9 shows a simulation map for the path length comparison test. Fig. 10 depicts an evaluation of the path length for every implemented navigation algorithm.

Every fixed node has a temperature and humidity sensor, while the mobile robot is equipped with temperature, humidity, light, solar radiation, $CO_2$ concentration and pressure sensors similar to [29]. Fixed sensor nodes are placed on every 100 meters and the mobile measuring station improves measurements with the ability to measure environmental parameters between the fixed nodes. By

**Table 8**
The average total weight and the number of fruit harvested.

| Tested plants | Average weight of fruit (with automation) | Average weight of fruit (without automation) | Average number of fruit per plant (with automation) | Average number of fruit per plant (without automation) |
|---|---|---|---|---|
| **Tomato** | 215 g | 185 g | 18 | 11 |
| **Capsicum** | 140 g | 120 g | 17 | 12 |
| **Cucumber** | 80 g | 60 g | 15 | 12 |

using this concept we can build a temperature, humidity or even light map of the object in a good resolution and we can determine if any malfunction appears (like plastic film damage or bio-light malfunction, etc.).

As we can see in Fig. 10, the developed RSSI_PotField navigation algorithm finishes the navigation task with the shortest path length.

## 7. Discussion

Using an automated greenhouse control system it is possible to expand the production cycle of the crops inside the greenhouse, but we must take into consideration the energy usage factor. If we spend too much energy to create ideal conditions for the crops, the production costs will drastically rise. This is the reason why it is not suggested to grow plants in the period from December 15 to February 15. Excellent light, moderate heating costs and good prices annually demonstrate this is the best time for greenhouse tomato production. Tomato plants grow best when the night temperature is maintained at 16 - 18 °C. Temperatures below 16 °C will prevent normal pollination and fruit development. For example, tomatoes are a warm season vegetable crop and they grow best under conditions of high light and warm temperatures. Low light in a fall or winter greenhouse, when there is less than 15% of summer light levels, greatly reduces fruit yield when heating costs are highest. For this reason, it is difficult to recommend that a greenhouse operator should grow and harvest fruit from December 15 to February 15. Based on a few years of experience, tomato production is most successful in the spring.

In warm or hot outdoor conditions, tomato greenhouses must be ventilated to keep temperatures below 35 °C. High temperatures not only affect the leaves and fruit, but increased soil temperatures also reduce root growth. Table 8 gives a comparison of the

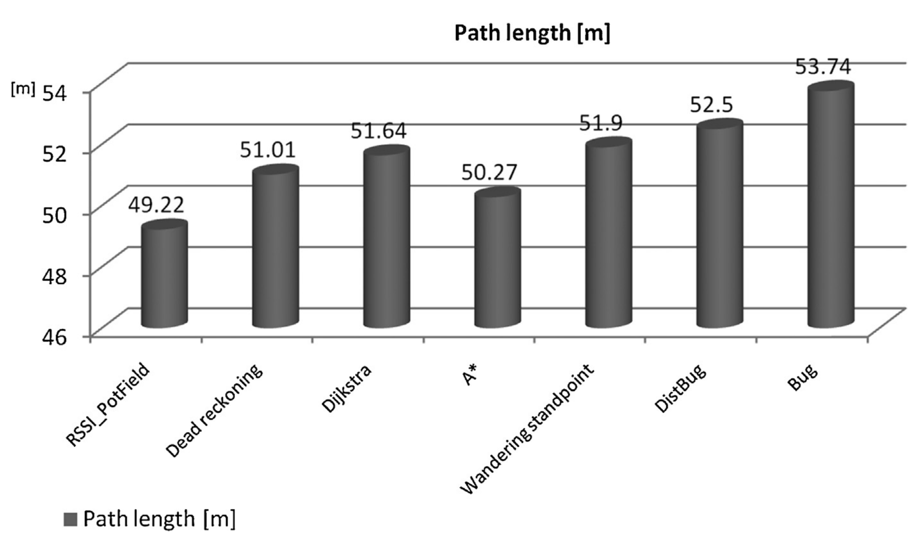


**Fig. 10.** Path length.

average total weight and the number of fruit harvested with the developed control system based on the WSN and mobile measuring station and with a classical one-point measuring control system. Success in greenhouse plants depends completely on fruit yield. Yields of 20–25% gain per plant are very good for annual costs. One of the main goals of the project is to develop a stabilized universal greenhouse control system capable of fast adaptive control in various conditions. The research area inside the greenhouse is the navigation of a wirelessly controlled mobile measuring station.

## 8. Conclusion

In this work, we analyze the need for the development of models for environmental management due to the fact that the stationary measuring points can be replaced by an autonomous mobile measuring station. These assumptions imply the need for addressing autonomous navigation of the mobile measuring station in an unknown dynamic environment, as well as wirelessly collected climatic parameters by using sensor networks. In addition, there is a need for developing an expert system based on fuzzy multiple criteria decision making and an optimal management strategy of choice for the greenhouse as well as the development of methods for data fusion in real time. The proposed model for environmental management using mobile monitoring stations compared to conventional systems has the ability to control microclimate conditions by zones, the possibility of generating a temperature map of the object, the object damage detection based on the temperature map. This change in management microclimates led to certain changes, which are reflected in an increasing number of control strategies, which is one of the most important elements in the developed model. Results of the analysis of the behavioral control system indicated the need for special attention to address the very stage of decision-making that brings a stable microclimate with minimal energy expended. Based on defined subjects, research includes the basic hypothesis, which is reflected in the possibilities of using a mobile measuring station instead of stationary measurement points. The control system has been successfully implemented; however, there are still possibilities for further improvements mentioned in Chapter VI. In order to carry out verification of the proposed model for environmental management by an autonomous mobile measuring station, comparative results of experimental measurements of various climate parameters are given. The analysis of the results indicates accuracy and robustness of the model.

## References

[1] A. Pawlowski, J.L. Guzman, F. Rodríguez, M. Berenguel, J. Sánchez, S. Dormido, Simulation of Greenhouse Climate Monitoring and Control with Wireless Sensor Network and Event-Based Control, Sensors 9 (1) (2009) 232–252.
[2] L. Bencini, D. Di Palma, G. Collodi, A. Manes, G. Manes, "Wireless Sensor Networks for On-Field Agricultural Management Process, Wireless Sensor Networks: Application - Centric Design", Yen Kheng Tan (Ed.), InTech, 2010, Available from: http://www.intechopen.com/books/wireless-sensor-networks-application-centric-design/wireless-sensor-networks-for-on-field-agricultural-management-process
[3] J. Simon, Optimal Microclimatic Control Strategy Using Wireless Sensor Network and Mobile Robot, Acta Agriculturae Serbica 18 (36) (2013) 3–12.
[4] R. Langer, L. Coelho, G. Oliveira, K-Bug, a New Bug Approach for Mobile Robot's Path Planning, in: Proc. of the IEEE Int. Conference on Control Applications, Singapore, 1-3 October, 2007, pp. 403–408.
[5] C. Serodio, J.B. Cunha, R. Morais, C.A. Couto, J.L. Monteiro, A Networked Platform for Agricultural Management Systems, Computers and Electronics in Agriculture 31 (1) (2001) 75–90.
[6] X. Feng, T. Yu-Chu, S. Yanjun, S. Youxian, Wireless Sensor/Actuator Network Design for Mobile Control Applications, Sensors 7 (10) (2007) 2157–2173.
[7] G. Liu, Y. Ying, Application of Bluetooth Technology in Greenhouse Environment, Monitor and Control, J. Zhejiang Univ., Agric. Life Sci. 29 (1) (2003) 329–334.
[8] M. Mizunuma, T. Katoh, S. Hata, Applying IT to Farm fields, A Wireless LAN. NTT Tech. Rev. 1 (2003) 56–60.
[9] R. Siegwart, R. Illah, Introduction to Autonomous Mobile Robots, The MIT Press Cambridge, London, England, 2004.
[10] S.J.E. Mohd, A.H. Adom, A.Y. Shakaff, M.A. Shuib, Real-Time Wireless Agricultural Ecosystem Monitoring for Cucumus Melo.l Cultivation on Natural Ventilated Greenhouse, International Journal of Scientific and Research Publications 3 (11) (2013) 1–6.
[11] J. Simon, G. Martinović, Navigation of Mobile Robots Using WSN's RSSI Parameter and Potential Field Method, Acta Polytechnica Hungarica, Journal of Applied Sciences 10 (4) (2013) 107–118.
[12] C.H. Chiang, J.S. Liu, Y.S. Chou, Comparing Path Length by Boundary Following Fast Matching Method and Bug Algorithms for Path Planning, Opportunities and Challenges for Next-Generation Artificial Intelligence 214 (2009) 303–309.
[13] L. Gonda, C. Cugnasca, A Proposal of Greenhouse Control Using Wireless Sensor Networks, in: Proc. of 4th World Congress Conference on Computers in Agriculture and Natural Resources, Orlando, FL, USA, 24-26 July, 2006, pp. 229–233.
[14] O. Khatib, The Potential Field Approach and Operational Space Formulation in Robot Control, in: Proc. of 4th Yale Workshop on Applications of Adaptive Systems Theory, Yale University, New Haven, CT, USA, 1985, pp. 208–214.
[15] M.J. Matarić, The Robotics Primer, The MIT Press, London, England, 2007.
[16] K. Kreichbaum, Tools and Algorithms for Mobile Robot Navigation with Uncertain Localization, California Institute of Technology, USA, 2006, PhD Thesis.
[17] O. Khatib, Real-Time Obstacle Avoidance for Manipulators and Mobile Robots, Int. J. of Robotic Research 5 (1) (1986) 90–98 (2006).
[18] J.S. Esteves, A. Carvalho, C. Couto, Generalized Geometric Triangulation Algorithm for Mobile Robot Absolute Self-Localization, in: Proc. of 2003 IEEE Int. Symposium on Industrial Electronics, Rio de Janeiro, Brazil, 09-11 June, 2003, pp. 346–351.
[19] Gy. Mester, Wireless Sensor-based Control of Mobile Robot Motion, in: Proc. of 7th IEEE Int. Symposium on Intelligent Systems and Informatics 2009, Subotica, Serbia, 24-26 September, 2009, pp. 81–84.
[20] J. Simon, G. Martinović, Web Based Distant Monitoring and Control for Greenhouse Systems Using the Sun SPOT Modules, in: Proc. of 7th IEEE Int. Symposium on Intelligent Systems and Informatics 2009, Subotica, Serbia, 24-26 September, 2009, pp. 1–5.
[21] Y. Takahashi, T. Komeda, H. Koyama, Development of Assistive Mobile Robot System: Amos, Advanced Robotics 18 (5) (2004) 473–496.
[22] I. Matijevics, J. Simon, "Improving Greenhouse's Automation and Data Acquisition with Mobile Robot Controlled System via Wireless Sensor Network, Wireless Sensor Networks: Application - Centric Design", Yen Kheng Tan (Ed.), InTech, 2010. Available from: http://www.intechopen.com/books/wireless-sensor-networks-application-centric-design/improving-greenhouse-s-automation-and-data-acquisition-with-mobile-robot-controlled-system-via-wirel
[23] T.L. Saaty, The Analytic Hierarchy Process, Mc Graw-Hill, New York, USA, 1980.
[24] A. Sriraman, R.V. Mayorga, A Fuzzy Inference System Approach for Greenhouse Climate Control, Environmental Informatics Archives 2 (1) (2004) 699–710.
[25] T.C. Wang, Y.H. Chen, Applying fuzzy linguistic preference relations to the improvement of consistency of fuzzy AHP, Information Sciences 178 (19) (2008) 3755–3765.
[26] E. Albayrak, Y.C. Erensal, Using Analytic Hierarchy Process (AHP) to Improve Human Performance: an Application of Multiple Criteria Decision Making Problem, Journal of Intelligent Manufacturing 15 (4) (2004) 491–503.
[27] O.S. Vaidya, S. Kumar, Analytic Hierarchy Process: an Overview of Applications, European Journal of Operation Research 169 (1) (2006) 1–29.
[28] V. Lumelsky, A. Stepanov, Path Planning Strategies for a Point Mobile Automaton Moving Amidst Unknown Obstacles of Arbitrary Shape, Algorithmica 2 (1) (1987) 403–430.
[29] J. Simon, G. Martinović, Distant Monitoring and Control for Mobile Robots Using Wireless Sensor Network, in: Proc. of 10th Int. Symposium of Hungarian Researchers on Computational Intelligence and Informatics, Budapest, Hungary, 12-14 Nov, 2009, pp. 1–9.