Research Article

Lifetime Prediction for a Cell-on-Board (COB) Light Source Based on the Adaptive Neuro-Fuzzy Inference System (ANFIS)

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Predicting the lifetime of a LED lighting system is important for the implementation of design specifications and comparative analysis of the financial competition of various illuminating systems. Most lifetime information published by LED manufacturers and standardization organizations is limited to certain temperature and current values. However, as a result of different working and ambient conditions throughout the whole operating period, significant differences in lifetimes can be observed. In this article, an advanced method of lifetime prediction is proposed considering the initial task areas and the statistical characteristics of the study values obtained in the accelerated fragmentation test. This study proposes a new method to predict the lifetime of COB LED using an artificial intelligence approach and LM-80 data. Accordingly, a database with 6000 hours of LM-80 data was created using the Neuro-Fuzzy (ANFIS) algorithm, and a highly accurate lifetime prediction method was developed. This method reveals an approximate similarity of 99.8506% with the benchmark lifetime. The proposed methodology may provide a useful guideline to lifetime predictions of LED-related products which can also be adapted to different operating conditions in a shorter time compared to conventional methods. At the same time, this method can be used in the life prediction of nanosensors and can be produced with the 3D technique.

1. Introduction

Before the 1990s, LEDs were used in backlighting, communication, healthcare services, and signage and accent lighting systems especially thanks to their small (<10 mm) size [1, 2]. With the correct design, they offer the energy saving advantages of higher energy efficiency with lower voltage (usually <4 volts) and operation at low currents (usually <700 mA) with lower power consumption [3]. LED lighting fixtures are superior to traditional light sources with their properties such as saving energy (high efficiency), long life (50,000-100,000 hours), smaller size, perfect on/off response, low-temperature lighting, and being free of environmentally hazardous mercury (Hg) [4, 5]. Their on/off response time of microseconds, a wide range of color temperatures (3200-12,000 K) that is controllable, and a wide range of operating temperatures (20-950°C) guarantee high performance [6].

Usage of high-power white LEDs (HPLEDs) in light fixtures is currently a subject of extensive research, and HPLEDs have an increasing market share thanks to their environmentally friendly features, crucially important to help prevent global warming [7, 8].

The main limitation of the lighting fixtures of LED semiconductor components is the low power of single-chip diodes and the resulting low luminous flux. Manufacturers of light fixtures tried and solved this problem by creating a matrix structure with multiple single-chip LEDs [9, 10]. The product of fixing a multichip LED on a surface and covering it with a phosphorus-silicon mixture based on traditional filling technology is the COB (cell on board), a high-brightness, high-power white light that can be used indoors and outdoors [11]. This technology makes it possible to place multichips in a small area in order to create a multichip LED structure [12]. LED lighting fixtures of approximately 500 W power.
and 60,000 lm luminous flux can be produced by securing good thermal conductivity with the help of modern thermal conductive adhesives [13, 14].

The COB technology allows the side-by-side mounting of LED chips directly on a substrate or circuit board. This package design enables higher power intensity [15]. As LED chips are very closely spaced, designers must first optimize the distance between them to ensure an ideal balance of their thermal and optical properties [16, 17]. A LED array can be formed with two different methods. The first one is to line a printed circuit board (PCB) with high-power LED packages of the surface mount type (SMT). The other is to directly form a matrix with the chips on a PCB (these are called a COB array) [18]. There are two types of COB packages: ceramic substrate and metal substrate [19].

Nowadays, commercial demands for LED-containing fixtures in terms of lumen degradation are based entirely on the data from LM-79 and LM-80 and the TM-21 calculations [20]. IES LM-80-08 is an approved method for measuring the lumen values of LED lighting sources. The IES standard TM-21-11 is the most common method used to predict the lifetime of LED fixtures. For reliable long-term predictions, at least 6000 hours of testing are needed with LM-80 [21, 22]. The mean value for the normalized light output values from the LM-80 report is used, and a nonlinear regression is performed for a lifetime prediction model [20].

Figure 1 shows the change occurring in lifetime L (luminous flux) of the LED equipment over time. The formula called \( B_{50} - L_{70} \) means that 50% of the lumen output \( (B_{50}) \) is smaller than 70% \( (L_{70}) \) of the baseline. Lamp manufacturers perform lifetime testing on their products and define the lamp’s lifetime as the length of time that the light output drops below \( L_{70} \) in 50% of the testing time [24]. \( L_{70} \) and \( L_{85} \) are mostly preferred for outdoor applications, whereas \( L_{90} \) is preferred for indoor applications. In some lighting products that do not require precise lighting, \( L_{50} \) is also considered and used as a design parameter [23].

Qu et al. proposed a lifetime prediction method based on an accelerated distortion test and statistical data on lifetime [23]. Sun et al. used both the structure of the LED and the impact of the driver on the light source [2], and Li et al. used the Weibull distribution to determine the error rate of the prediction method [24]. Chen et al. presented an online test method at a test temperature of 125°C [25]. Park and Kim used the gamma model to predict the service life of LEDs [5], and Zhang et al. estimated the mean time to failure (MTTF) using exponential distribution [26]. Liu et al. studied the ANN distribution for temperature and lifetime in multi-chip LEDs [27], and Alfaro et al. used the thermally connected FEM [28]. Niu et al. studied the effects of LED driver Al-Cap core on life parameters [7]. Wang and Chu performed accelerated degradation testing (ADT) for light bars used in laptops [29]. Hao et al. performed the gradual aging test based on the Nelson model [30], and Wang and Lu used the degradation-data-driven method (DDD) to predict the lifetime of HP white LEDs [6].

The lifetime calculations for LED light sources were previously performed using conventional methods; however, AI-based calculation methods are more and more employed in recent years. In this study, an innovative method is proposed to predict the lifetime of a COB LED light source that is in the process of being introduced to the market. The proposed technique uses LM-80 data obtained in accordance with the IES TM-21-11 Lifetime Prediction Method to develop a prediction method based on AI (artificial intelligence). In line with the method developed, a data set for training and testing was created for ANFIS based on the results of measurements performed for 6000 hours. The developed ANFIS architecture allows for a high-accuracy lifetime prediction for the COB LED. This article is organized as follows: In the first part, the structure of the COB LED and semiconductor lifetime prediction methods are explained. The second part is dedicated to elaborating the COB LED used in the study, the lifetime prediction method, and the ANFIS structure. The lifetime prediction method developed for the selected COB LED lamp and the results obtained are described in the third part, and the last part concludes this study.

2. Methodology and Calculations of COB LED \( L_{70} \)

For this project, a technically and economically advanced system was developed due to the high density of large buildings in Istanbul. Accordingly, energy-production estimates were obtained using the PV+ SOL program based on 1-year sunshine data for Istanbul. The real-time application was then compared with the production data. PV plants with 23.68 kW of DC power were installed on the roofs of three buildings with similar features in the same location (in the Başakşehir District of Istanbul). All three PV plants (fixed-angle, adjustable-angle, and automatic solar-tracking systems) were mounted on the buildings, and each was comprised of 320 W polycrystalline PV panels with 16.5% efficiency.

An EV charging station enables the recharging of EVs using external energy sources. Although such systems are usually connected to the grid, they may also be connected to renewable energy sources. EV charging stations draw high current during operations and also generate harmonics due
to the structure of their electronic circuits. Therefore, EV charging stations should have filtering and compensation systems so as to conform to standards. Overcurrent, short-circuit, and residual-current protections should be present in every electrical device; these features are available as the standard for these devices. Furthermore, these stations should have a software infrastructure for processing the charging data because of the need for energy sales at the stations. A communication system that is capable of sharing data with the relevant companies and processing data for the user’s account is also needed. This communication can be provided by systems such as Wi-Fi, GPRS, RS-485, and TCP/IP. EV charging stations also often have hardware such as radio-frequency identification card readers for users. The standards for charging stations vary by region. Prediction of the useful lifetime of light power is based on a standard procedure. The LM-80-08 standard, published by the Illuminating Engineering Society of North America (IESNA), is used to predict the lifetime of light sources with the help of an exponential regression equation calculated on the basis of the reduction of initial luminous flux [31]. The traditional method of estimating lifetime is the regression model [5].

What makes this study stand out from others on the same theme can be explained as follows:

1. In recent studies performed to predict the lifetime of LEDs, the Fuzzy Logic and Neural Network algorithms from among the AI methods were used. This study uses the Adaptive Neuro-Fuzzy Inference System (ANFIS) for COB LED lifetime prediction.

2. Most of the work performed is based on techniques used exclusively for a tester. The method developed in this study provides fast and accurate results for all semiconductor lighting products with an LM-80-08 report.

This study is aimed at developing a new method for the safe and fast determination of the lifetime of the COB LED light source, which has been used for lighting purposes in the last five years. The block diagram of the methodology is given in Figure 2.

Firstly, LM-80 test data obtained with at least 6000 hours of laboratory measurement of COB LED were obtained from the relevant company. In the study, COB LED with the product code of NVELJ048Z of the Nichia Corporation was used.

In the second stage, the COB LED $L_{70}$ lifetime was calculated using the exponential function from the catalog data for the 80°C junction temperature.

In the third stage, three ANFIS models with different membership function types were created for detailed analysis of life expectancy. In order to find the most accurate approach according to the type of data obtained, models were created using the triangle, gbell, and Gaussian membership functions.

In the last stage, the lifetimes were calculated according to the ANFIS model. The life expectancies found using the exponential function and the ANFIS models were compared with the reference value.

2.1. Test Device. The research object selected for this study was the NVELJ048Z model white COB LED (Table 1) of Nichia Corporation.

A chip made of indium gallium nitride (GaN) was combined on the metal interconnection layer, and a ceramic substrate of high thermal conductivity 2 W/(m·K) was used to increase heat distribution [5, 32].

2.2. Lumen Maintenance Degradation ($L_{70}$). The IES TM-80-08 “Measurement of the Luminous Flux Maintenance in LED Light Sources” was further improved to develop and publish the IES TM-21-11 “Lifetime Prediction Method” standard in 2011, which helped to estimate long-term luminous flux drop with LM-80 data [33].

Table 1: Technical specifications of the Nichia NVELJ048Z COB LED used in the study [32].

| Item                        | Symbol | Absolute maximum rating | Unit |
|-----------------------------|--------|-------------------------|------|
| Forward current             | $I_F$  | 1000                    | mA   |
| Pulse forward current       | $I_{FP}$ | 1500              | mA   |
| Allowable reverse current   | $I_R$  | 85                      | mA   |
| Power dissipation           | $P_D$  | 38.7                    | W    |
| Operating temperature       | $T_{opr}$ | -40–105         | °C   |
| Storage temperature         | $T_{stg}$ | -40–100            | °C   |
| Junction temperature        | $T_J$  | 150                     | °C   |

Figure 2: Block diagram of the methodology.
Table 2: Charging-station information reliability requirement of LED light source and LAMP in current standards [23].

| Test item               | Standards          | Descriptions                                                                 | Remark               |
|-------------------------|--------------------|-------------------------------------------------------------------------------|----------------------|
| Lumen maintenance       | IES-LM-80-08/Energy Star | 6000 hr. life test at 3 different case temperatures: 55°C and 85°C, as defined by the manufacturer | 10 samples by Energy Star |
| Rapid-cycle stress test | Energy Star        | Cycle times: 2 minutes on, 2 minutes off. Lamp cycled once for every two hours of required minimum $L_{70}$ life | 10 samples by Energy Star |
| Lumen maintenance       | IEC/PAS 62612      | 6000 hits life test at 45°C ambient temperature                              | Sample size 10       |
| Rapid-cycle stress test | IEC/PAS 62612      | Cycle times: 30 sec. on, 30 sec. off. Lamp cycled once for every two hours of required minimum $L_{70}$ life |                       |
| Thermal shock           | IEC/PAS 62612      | -10°C~50°C 1 hr. dwell 5 cycles                                              |                      |

Figure 3: Calculation lifetime ($L_{70}$) using exponential function.

Figure 4: The ANFIS model with two inputs, two rules, and one output [35, 36].

According to the IES TM-21-11 Lifetime Prediction Method Standard, the luminous flux reduction is estimated using the LM-80 data. Under this standard, a minimum of 6000 hours of laboratory measurements are performed and this value is considered equal for the lifetime of the light fixture; however, the fixture’s optical design and electrical elements should also be factored in as they affect the luminous flux [34].

The lifetime of light sources is described as the time until the lumen output of the lamp is reduced to less than 70% of the baseline as a result of the decrease in lumen or the deterioration caused by its electronic components [24]. Table 2 shows the change of lifetime in different operating modes over the lifetime of the lumen output of an LED light source rather than measuring the lamp’s entire lifetime. Nowadays, the IES LM-80 test data are a common requirement for lamps containing a LED light source in the market to simplify the evaluation of LED efficiency and state the product’s lifetime. On the other hand, the LM-80 test reports are generally carried out below typical constant driving current values and specific conditions with at least three different ambient temperatures (55°C, 85°C, and one manufacturer-defined value) [23].

After the LM-80 test procedure, TM-21 is generally used for luminous maintenance with the mean values of LM-80 data, and lumen maintenance data can be specified by means of the least squares method using the exponential light replacement formulation:

$$\Phi_i(t) = Be^{-\beta_i t},$$

where $t$ is the working time in hours, $\Phi_i(t)$ is the average normalized luminous flux in the conditional state at time $t$, $B$ is an estimated primary constant obtained from the least squares equation. $\beta_i$ is a decay rate constant obtained from the Arrhenius formula incorporated with the ambient temperature ($T_{a}$):

$$\beta_i = A_0e^{-\frac{E_a}{K T_{a}}},$$

where $a$ is the decay rate constant obtained from the least squares equation, $\beta$ is the shape factor [20, 26].

For each current and temperature, the $L_{70}$ value, i.e., $\Phi = 0.7$, can be found by means of the average normalized light output:

$$L_{70} = \left(\frac{-\ln (0.7)}{\alpha}\right)^{1/\beta}.$$  

Considering the $T_{ji}$-related appropriate junction temperature ($T_{ji}$), the Arrhenius equation can be formulated as follows:

$$\beta_i = A_0e^{-\frac{E_a}{K T_{ji}}},$$

where $A_0$ is an exponential factor, $E_a$ is the activation energy (eV), $K$ is the Boltzmann constant.
and Fuzzy Logic. It combines the performance. It is very successful in solving nonlinear problems.

Fuzzy Logic with ANN on the combination of Artificial Neural Networks (ANN) and Fuzzy Logic. In fact, ANFIS is a rule-based model such as the Fuzzy Inference System (FIS). The biggest challenge in FIS is to define a rule base [35–37]. Jyh-Shing and Jang suggested an optimization of the FIS parameters through the use of ANN as a solution [38]. In this method, ANN promotes decision-making with a Takagi-Sugeno type “if, then” rule table. The linguistic expressions of a Sugeno type fuzzy model with two inputs as follows [35–38]:

\[ f_i = p_i x + q_i y + r_i, \]

where \( x \) and \( y \) are the fuzzy sets; \( f_i \) is the output function; and \( p_i, q_i, \) and \( r_i \) are the design parameters determined at the training phase [35, 36].

The ANFIS model consists of 3 layers (Figure 4). The first one is the fuzzification layer. It determines the membership value of each input. The nodes in the input layer are expressed as follows:

\[ o^i_l = \mu_{X_l}(x), \quad \text{for } i = 1, 2. \]
It is determined according to the selected membership function. It can be a triangle, a trapezoid, a bell, or a Gaussian curve [35–38].

The second layer provides the activation of the fuzzy rules, and it is where the data from the first layer is multiplied [35–38]:

\[ o_i^2 = w_i = \mu_X(x) \times \mu_Y(y), \quad \text{for } i = 1, 2. \] (8)

The third one is the normalization layer, and it provides the normalization of the firing strength of the fuzzy rules [35–38]:

\[ o_i^3 = \tilde{w}_i = \frac{w_i}{w_1 + w_2}, \quad \text{for } i = 1, 2. \] (9)

The fourth layer is the defuzzification layer. It is obtained by multiplying the linear function or the constant determined for each rule through the normalized firing strength [35–38]:

\[ o_i^4 = \tilde{w}_i \times f_i = \tilde{w}_i \times (p_x + q_y + r_i) \quad \text{for } i = 1, 2. \] (10)

The fifth layer is where all outputs are summed [35–38]:

\[ o_i^5 = \sum \tilde{w}_i \times f_i, \quad \text{for } i = 1, 2. \] (11)

ANFIS also has two adaptation layers. Adaptation is achieved during the training phase of ANFIS through the
adjustment of the prerequisite parameters in the first layer and the result parameters in the fourth. The Hybrid Learning Algorithm consists of two stages. In the forward pass, the prerequisite parameters remain constant, and the result parameters are defined according to the least squares method. In the backward pass, the result parameters are kept constant, error rates are back propagated, and the prerequisite parameters are adjusted with a gradual decrease [36, 37].

3. Experimental Results and Discussion

The white COB LED with the model number NVELJ048Z is manufactured by the Nichia Corporation. IES published a standard IES LM-80-08 in 2008 to define the methodology of light output measurements for the LED light source. This is a practice widely accepted by the LED light source manufacturing and lighting industries. LEDs were tested at three different temperatures (55°C, 85°C, and 105°C) for 6000 hours [32].

The LM-80-08 test report for the white COB LED with model number NVELJ048Z, based on the measurements carried out in the Nichia Corporation LED Testing Laboratory, are presented in Table 3.

The requested lifetime $L$ is generally not measured. The Illumination Engineers Society (IES) [38] assigns the measurement methods as per the industry norm IES.

### Table 5: The best performance parameter of ANFIS models.

| Model | Input membership function type | Number of membership function | Output membership function type | RMSE (training) | RMSE (testing) | $R^2$ (training) | $R^2$ (testing) |
|-------|-------------------------------|-------------------------------|--------------------------------|-----------------|----------------|-----------------|-----------------|
| Md1   | Triangle                      | 6                             | Constant                       | 352.556         | 412.875        | 0.9974          | 0.9952          |
| Md2   | Gbell                         | 6                             | Constant                       | 935.428         | 914.820        | 0.9841          | 0.9827          |
| Md3   | Gauss                         | 7                             | Constant                       | 1579.06         | 1513.185       | 0.9722          | 0.9705          |

### Table 6: Md1 output vs. LED chip lifetime.

| Lifetime maintenance | 1500 mA/57.3°C Target | 1500 mA/57.3°C Output | 1500 mA/87.4°C Target | 1500 mA/87.4°C Output | 1140 mA/87.4°C Target | 1140 mA/87.4°C Output | 1140 mA/105.5°C Target | 1140 mA/105.5°C Output |
|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| $L_{98}$             | 4118.932              | 4068.596              | 2945.860              | 2888.466              | 4222.648              | 4152.667              | 4322.648              | 4338.818              |
| $L_{96}$             | 8322.795              | 8266.483              | 5952.463              | 5895.363              | 8532.367              | 8460.271              | 8848.185              | 8928.695              |
| $L_{94}$             | 12,615.171            | 12,558.250            | 9022.367              | 8969.501              | 12,932.822            | 12,864.213            | 13,458.395            | 13,533.553            |
| $L_{92}$             | 16,999.856            | 16,947.078            | 12,158.298            | 12,113.163            | 17,427.922            | 17,367.747            | 18,172.865            | 18,237.447            |
| $L_{90}$             | 21,480.923            | 21,436.299            | 15,363.154            | 15,328.740            | 22,021.820            | 21,974.300            | 22,955.184            | 23,044.732            |
| $L_{88}$             | 26,062.690            | 26,029.396            | 18,640.035            | 18,618.718            | 26,718.959            | 26,687.450            | 27,929.081            | 27,960.055            |
| $L_{86}$             | 30,749.799            | 30,730.022            | 21,992.257            | 21,985.717            | 31,524.090            | 31,510.932            | 32,978.486            | 32,988.384            |
| $L_{84}$             | 35,547.200            | 35,541.990            | 25,423.360            | 25,432.472            | 36,442.292            | 36,448.670            | 38,147.498            | 38,135.037            |
| $L_{82}$             | 40,460.214            | 40,469.309            | 28,937.143            | 28,961.850            | 41,479.016            | 41,504.773            | 43,440.420            | 43,405.717            |
| $L_{80}$             | 45,494.532            | 45,516.185            | 32,537.699            | 32,567.859            | 46,684.114            | 46,683.552            | 48,861.767            | 48,806.551            |
| $L_{78}$             | 50,656.343            | 50,678.008            | 36,229.418            | 36,280.652            | 51,931.890            | 51,989.501            | 54,416.229            | 54,344.129            |
| $L_{76}$             | 55,952.231            | 55,986.395            | 40,017.038            | 40,076.544            | 57,361.111            | 57,427.428            | 60,025.557            | 60,108.836            |
| $L_{74}$             | 61,389.370            | 61,419.204            | 43,905.687            | 43,968.023            | 62,935.171            | 63,002.231            | 65,944.794            | 65,858.507            |
| $L_{72}$             | 66,975.459            | 66,990.551            | 47,900.875            | 47,958.705            | 68,661.942            | 68,719.204            | 71,929.528            | 71,851.283            |
| $L_{70}$             | 72,718.941            | 70,875.766            | 52,008.574            | 50,741.645            | 74,550.044            | 72,705.949            | 76,103.018            | 76,012.892            |
Table 7: Mdl 2 output vs. LED chip lifetime.

| Lifetime maintenance | 1500 mA/57.3 °C Target | 1500 mA/87.5 °C Target | 1140 mA/87.4 °C Target | 1140 mA/105.5 °C Target |
|-----------------------|-------------------------|------------------------|------------------------|------------------------|
|                       | Output                  | Output                 | Output                 | Output                 |
| L₉₈                   | 4118.932                | 3818.217               | 2945.860               | 2783.437               |
| L₉₆                   | 8322.795                | 7889.633               | 5952.463               | 5683.255               |
| L₉₄                   | 12,615.171              | 12,352.778             | 9022.367               | 8862.082               |
| L₉₂                   | 16,999.856              | 17,012.808             | 12,158.298             | 12,181.137             |
| L₉₀                   | 21,480.923              | 21,690.503             | 15,363.154             | 15,512.773             |
| L₈₈                   | 26,062.690              | 26,289.418             | 18,640.035             | 18,788.298             |
| L₈₆                   | 30,749.799              | 30,844.624             | 21,992.257             | 22,032.690             |
| L₈₄                   | 35,547.200              | 35,507.528             | 25,423.360             | 25,353.793             |
| L₈₂                   | 40,460.214              | 40,447.607             | 28,937.143             | 28,872.310             |
| L₈₀                   | 45,494.532              | 45,721.041             | 32,537.699             | 32,628.263             |
| L₇₈                   | 50,656.343              | 51,203.237             | 36,229.418             | 36,532.892             |
| L₇₆                   | 55,952.231              | 56,634.208             | 40,017.038             | 40,401.028             |
| L₇₄                   | 61,389.370              | 61,728.828             | 43,905.687             | 44,413.736             |
| L₇₂                   | 66,975.459              | 66,269.116             | 47,900.875             | 47,263.386             |
| L₇₀                   | 72,718.941              | 70,138.976             | 52,008.574             | 50,019.641             |

Table 8: Mdl 3 output vs. LED chip lifetime.

| Lifetime maintenance | 1500 mA/57.3 °C Target | 1500 mA/87.5 °C Target | 1140 mA/87.4 °C Target | 1140 mA/105.5 °C Target |
|-----------------------|-------------------------|------------------------|------------------------|------------------------|
|                       | Output                  | Output                 | Output                 | Output                 |
| L₉₈                   | 4118.932                | 4047.894               | 2945.860               | 2858.584               |
| L₉₆                   | 8322.795                | 7507.493               | 5952.463               | 5346.754               |
| L₉₄                   | 12,615.171              | 11,950.713             | 9022.367               | 8541.899               |
| L₉₂                   | 16,999.856              | 17,031.934             | 12,158.298             | 12,194.742             |
| L₉₀                   | 21,480.923              | 21,256.159             | 15,363.154             | 15,876.080             |
| L₈₈                   | 26,062.690              | 26,839.843             | 18,640.035             | 19,236.212             |
| L₈₆                   | 30,749.799              | 31,032.743             | 21,992.257             | 22,236.295             |
| L₈₄                   | 35,547.200              | 35,109.318             | 25,423.360             | 25,142.358             |
| L₈₂                   | 40,460.214              | 39,600.678             | 28,937.143             | 28,333.281             |
| L₈₀                   | 45,494.532              | 44,858.880             | 32,537.699             | 32,061.290             |
| L₇₈                   | 50,656.343              | 50,792.038             | 36,229.418             | 36,268.263             |
| L₇₆                   | 55,952.231              | 56,844.226             | 40,017.038             | 40,548.521             |
| L₇₄                   | 61,389.370              | 62,304.681             | 43,905.687             | 44,413.736             |
| L₇₂                   | 66,975.459              | 66,968.888             | 47,900.875             | 47,523.797             |
| L₇₀                   | 72,718.941              | 69,929.003             | 52,008.574             | 49,810.105             |

Table 9: Lifetime prediction (L₉₀).

| Model type      | Lifetime (hrs.) |
|-----------------|-----------------|
| Reference       | 76,216.842      |
| Exponential     | 73,860.280      |
| Mdl 1           | 76,103.018      |
| Mdl 2           | 73,852.756      |
| Mdl 3           | 73,099.388      |

LM-80 [27]. It requires that the LED lamps are tested for at least 6000 hours with a sufficient number of samples and data. Many measurements are performed by LED producers and are under 10,000 hours. After that, the lifetime was estimated according to test report in the IES LM-80 with the exponential light exchange model as described by the standard IES TM-21 [32].

In this study, for the modeling of the ANFIS system, the light output maintenance values of the COB LED fixtures
were used. The required reference values for this were obtained from the relevant company report [27, 32]. Table 4 presents summary information on the current, temperature, luminous flux, and lifetime values of the tested LED fixtures.

As seen in Table 4, the designed ANFIS model had three input parameters: the current values, fixture temperature, and normalized luminous flux values of the COB LED fixtures (Figure 5). The drive current range was from 1.140 to 1.500 mA, whereas the temperature varied between 57.3°C and 105.5°C. Operating times corresponding to 98% to 70% of the initial luminous fluxes of COB LED fixtures constitute the output of the ANFIS model.

Of the total of 595 × 4 data, 479 × 4 were used for training and 118 × 4 for testing (Figure 6). A total of 6 (2 2 2) inputs, 2 fuzzy sets, and 8 rules were created for the first and second models. For the third model, a total of 7 (2 2 3) inputs and 2 fuzzy sets were used for the output, and 12 rules were created (Figure 7).

Inputs were fuzzified with the triangle, bell, and Gaussian membership functions, respectively (trimf, gbellmf, and gaussmf). Output membership function was selected as a “constant.” Models created with the hybrid learning algorithm were individually tested for all types of fuzzy sets. Table 5 shows the best obtained performance parameters.

FIS surfaces for the inputs and outputs of the models are presented in Figure 8.

When the models are compared, it is seen that the smallest RMSE value is obtained with Mdl 1 which used the triangular membership function. Bigger RMSE values were obtained in Mdl 3 and Mdl 2. For a better evaluation of the ANFIS model output values, the prediction times obtained with the values in Table 1 are provided in Tables 6–8.

4. Conclusion

Multiple factors affect the LED lifetime. Among them are LED’s operating time, temperature, and driving current. Differences are observed even in the same group of LED chips. An analysis of the results obtained shows that the LED lifetime decreases as the operating temperature increases. Nevertheless, an increase in the driving current at the same temperature reduces the LED lifetime. The remaining LED lifetime at the desired temperature and current values can be successfully predicted with the suggested ANFIS model. The aim of this study is to propose the new method which predicted the lifetime of high-power COB LED fixtures. In addition, this method can also be used in the life estimation of nanosensors and can be produced with 3D technology in the future. The data from Tables 6–8 can be summarized as follows:

(i) For Mdl 1, according to Table 6, when the operating current increases by about 32%, the lifetime decreases by about 40.1%. Moreover, it was seen that in the same model, operating temperature increases of about 18% and 31% caused a decrease in the lifetime by about 4.1% and 39.1%, respectively

(ii) For Mdl 2, according to Table 7, when the operating current increases by about 32%, the lifetime decreases by about 42.7%. Moreover, it was seen that in the same model, operating temperature increases of about 18% and 31% caused a decrease in the lifetime by about 4.4% and 40.9%, respectively

(iii) For Mdl 3, according to Table 8, when the operating current increases by about 32%, the lifetime decreases by about 45.3%. Moreover, it was found that in the same model, operating temperature increases of about 18% and 31% caused a decrease in the lifetime by about 4.8% and 42.4%, respectively

Table 9 shows the $L_{70}$ lifetime prediction values according to the obtained models. The product’s life expectancy (reference) value is 76216.842 hours in the catalog [32]. According to the classical calculation method (exponential function), the lifetime was found to be 73860.279 hours. Accordingly, the Mdl 1 results created with ANFIS was found to be close to the reference at the rate of 99.8506%. For Mdl 2, this value is 96.8982%; for Mdl 3, this value is 95.9097%. Consequently, it can be said that the most successful model is Mdl 1.

Data Availability

The dataset supporting the conclusions of this article are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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