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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}-L_{85} are mostly preferred for outdoor applications, whereas L_{90} is preferred for indoor applications. In some lighting projects 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 multichip LEDs [27], and Alfarog 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 (DDDM) 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.

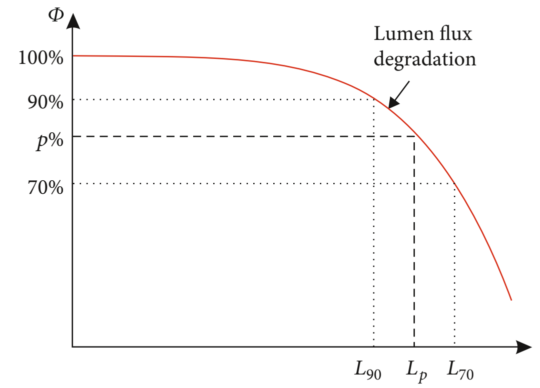

Figure 1: Luminous flux change curve for the LED light source based on time [23].

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

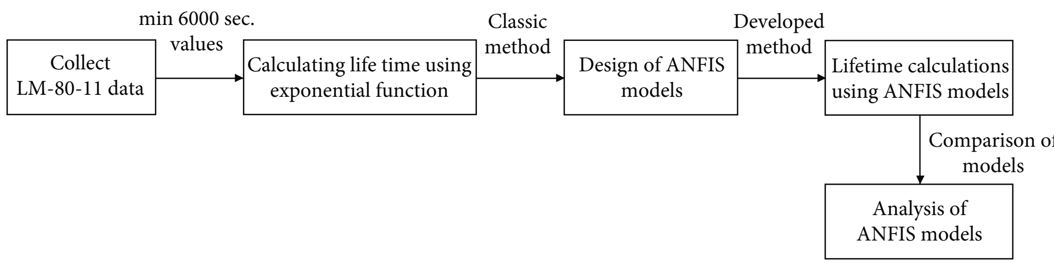

Figure 2: Block diagram of the methodology.

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

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 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	

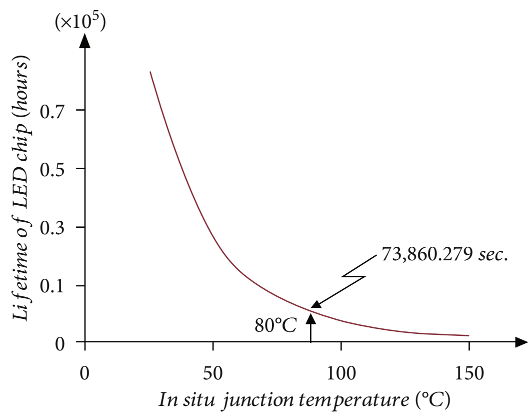

Figure 3: Calculation lifetime (L_{70}) using exponential function.

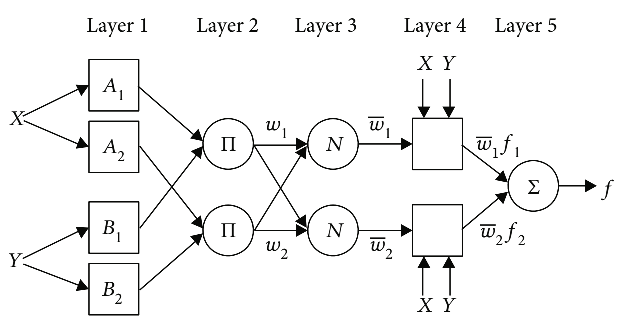

Figure 4: The ANFIS model with two inputs, two rules, and one output [35, 36].

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:

$$\Phi_i(t) = Be^{(-\beta_i t)}, \tag{1}$$

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. β_i is a decay rate constant obtained from the Arrhenius formula incorporated with the ambient temperature ($T_{a,i}$):

$$\beta_i = A_0 e^{(-E_a/K \cdot T_{a,i})}, \tag{2}$$

where α is the decay rate constant obtained from the least squares equation, β 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:

$$L_{70} = \left(\frac{-\ln(0.7)}{\alpha}\right)^{1/\beta}. \tag{3}$$

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

$$\beta_i = A_0 \mathrm{e}^{\left(-E_a/K \cdot T_{j,i}\right)}, \tag{4}$$

where A_0 is an exponential factor, E_a is the activation energy (eV), K is the Boltzmann constant

Table 3: Summary report for the Nichia COB LED LM-80-08 with model number NVELJ048Z [32].

Data set	Case temperature (T_S)	Ambient temperature (T_A)	Drive current (I_F)	Average current per die	Lumen maintenance at 10,000 hours	Chromaticity shift at 10,000 hours	TM-21 projection L_{70} (10 K)
1	55°C	>50°C	3300 mA	1100 mA	95.0%	0.0022	>55,000 hours
2	85°C	>80°C	2350 mA	783 mA	94.7%	0.0022	>55,000 hours
3	85°C	>80°C	3300 mA	1100 mA	94.4%	0.0024	>55,000 hours
4	105°C	>100°C	2350 mA	783 mA	94.0%	0.0022	>55,000 hours

Table 4: LED chip lifetime of light output maintenance.

Lifetime maintenance	1500 mA/57.3 °C	1500 mA/87.5°C	1140 mA/87.4°C	1140 mA/105.5°C
L_{98}	4118.932	2945.860	4222.648	4418.790
L_{96}	8322.795	5952.463	8532.367	8928.695
L_{94}	12,615.171	9022.367	12,932.822	13,533.553
L_{92}	16,999.856	12,158.298	17,427.922	18,237.447
L_{90}	21,480.923	15,363.154	22,021.820	23,044.732
L_{88}	26,062.690	18,640.035	26,718.959	27,960.055
L_{86}	30,749.799	21,992.257	31,524.090	32,988.384
L_{84}	35,547.200	25,423.360	36,442.292	38,135.037
L_{82}	40,460.214	28,937.143	41,479.016	43,405.717
L_{80}	45,494.532	32,537.699	46,640.114	48,806.551
L_{78}	50,656.343	36,229.418	51,931.890	54,344.129
L_{76}	55,952.231	40,017.038	57,361.111	60,025.557
L_{74}	61,389.370	43,905.687	62,935.171	65,858.507
L_{72}	66,975.459	47,900.875	68,661.942	71,851.283
L_{70}	72,718.941	52,008.574	74,550.044	78,012.892

$(8.6173 \cdot 10^{-5}\,\text{eV/K})$, $T_{j,i}$ is the ambient temperature, $T_{a,j}$ is the absolute T_j.

$$L_p = \frac{\ln\left(100(B/p)\right)}{\beta_i} = \frac{\ln\left(100(B/p)\right)}{A_0 e^{\left(-E_a/K\cdot T_{j,i}\right)}}, \tag{5}$$

where p is the percentage of the first maintained luminous output. The $T_{j,i}$ stated here is the instaneous junction temperature of the LED under the working ambient conditions obtained with $T_{j,i}$.

In Figure 3, the lifetime curve is shown for Nichia brand NVELJ048Z model COB LED. Using equation (5), the COB L_{70} lifetime was found to be 168,844.6 hours, according to the catalog values and the calculation for the 80°C junction temperature.

2.3. Adaptive Neuro-Fuzzy Inference System. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a model based on the combination of Artificial Neural Networks (ANN) and Fuzzy Logic. It combines the flexible adaptability of Fuzzy Logic with ANN's successful classification performance. It is very successful in solving nonlinear problems. 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 x and y are as follows [35–38]:

$$\begin{aligned} &\text{if } x \text{ is } X_1 \text{ and } y \text{ is } Y_1 \text{ then } f_1 = p_1 x + q_1 y + r_1, \\ &\text{if } x \text{ is } X_2 \text{ and } y \text{ is } Y_2 \text{ then } f_2 = p_2 x + q_2 y + r_2, \end{aligned} \tag{6}$$

where X_i and Y_i 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 5 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:

$$o_i^1 = \mu_{X_i}(x), \quad \text{for } i = 1, 2. \tag{7}$$

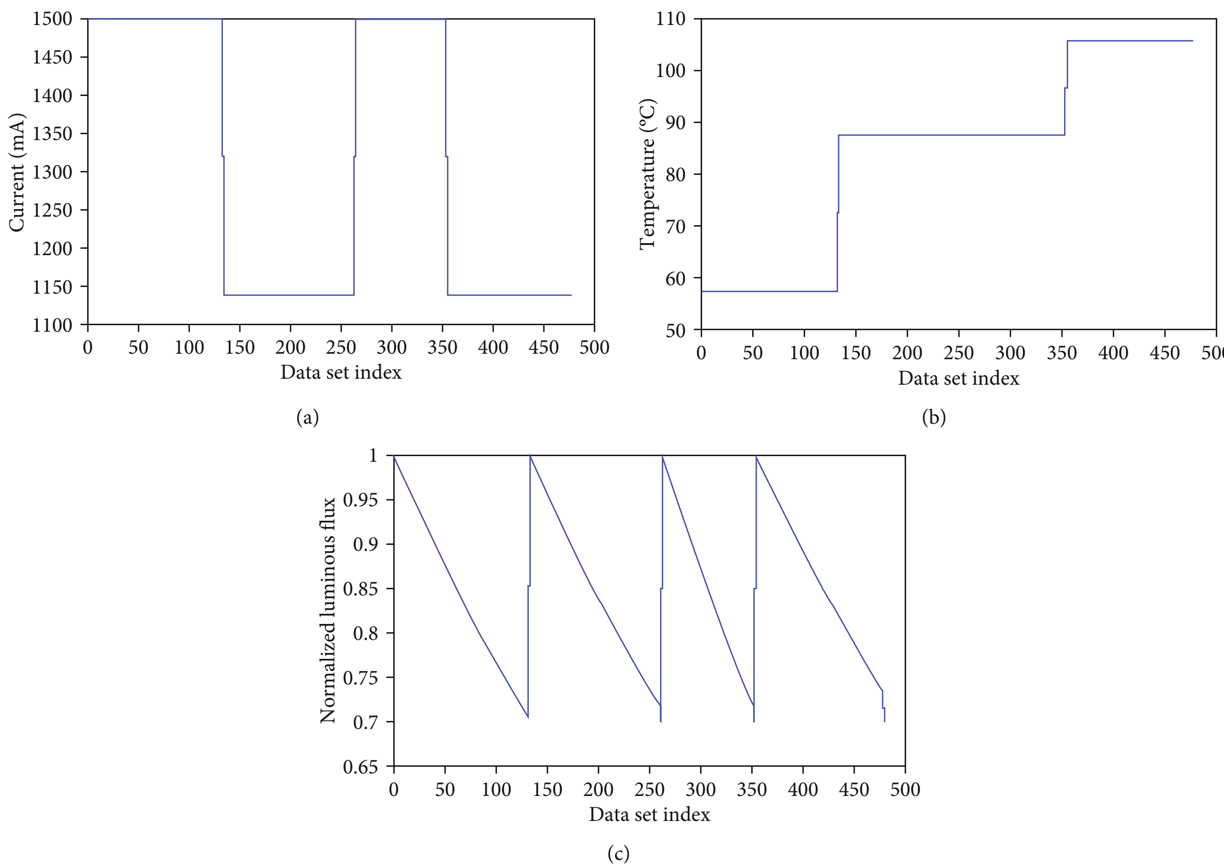

Figure 5: Inputs for ANFIS: (a) drive current, (b) operating temperature, and (c) normalized luminous flux.

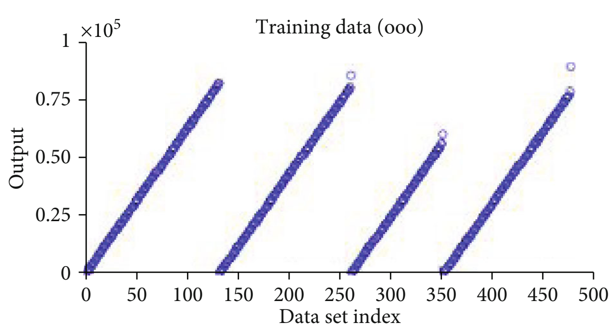

Figure 6: Training output data.

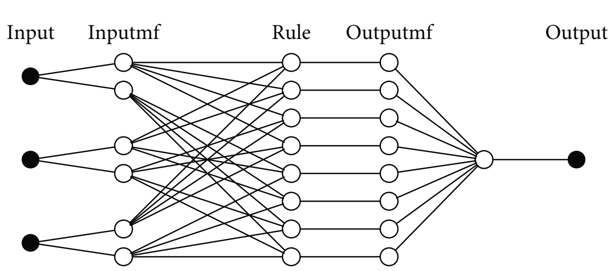

Figure 7: Proposed ANFIS model.

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]:

$$o_i^2 = w_i = \mu_{X_i}(x) \times \mu_{Y_i}(y), \quad \text{for } i = 1, 2. \tag{8}$$

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

$$o_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad \text{for } i = 1, 2. \tag{9}$$

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]:

$$o_i^4 = \bar{w}_i \times f_i = \bar{w}_i \times (p_i x + q_i y + r_i) \quad \text{for } i = 1, 2. \tag{10}$$

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

$$o_i^5 = \sum \bar{w}_i \times f_i, \quad \text{for } i = 1, 2. \tag{11}$$

ANFIS also has two adaptation layers. Adaptation is achieved during the training phase of ANFIS through the

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 (testing)
Md1 1	Triangle	6	Constant	352.556	412.875	0.9974	0.9952
Md1 2	Gbell	6	Constant	935.428	914.820	0.9841	0.9827
Mdl 3	Gauss	7	Constant	1579.06	1513.185	0.9722	0.9705

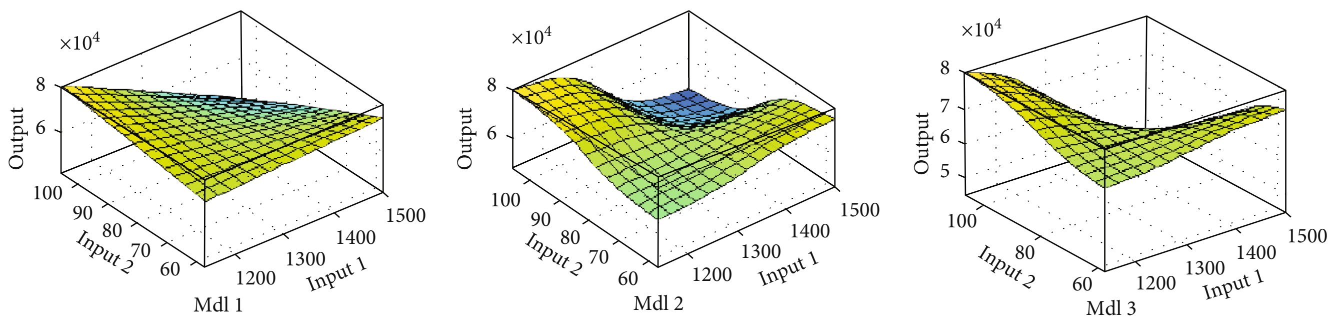

Figure 8: FIS surfaces of the proposed models.

Table 6: Mdl 1 output vs. LED chip lifetime.

Lifetime maintenance	1500 mA/57.3°C Target	1500 mA/57.3°C Output	1500 mA/87.5°C Target	1500 mA/87.5°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	4418.790	4338.818
L_{96}	8322.795	8266.483	5952.463	5895.363	8532.367	8460.271	8928.695	8848.185
L_{94}	12,615.171	12,558.250	9022.367	8969.501	12,932.822	12,864.213	13,533.553	13,458.395
L_{92}	16,999.856	16,947.078	12,158.298	12,113.163	17,427.922	17,367.747	18,237.447	18,172.865
L_{90}	21,480.923	21,436.299	15,363.154	15,328.740	22,021.820	21,974.300	23,044.732	22,995.184
L_{88}	26,062.690	26,029.396	18,640.035	18,618.718	26,718.959	26,687.450	27,960.055	27,929.081
L_{86}	30,749.799	30,730.022	21,992.257	21,985.717	31,524.090	31,510.932	32,988.384	32,978.486
L_{84}	35,547.200	35,541.990	25,423.360	25,432.472	36,442.292	36,448.670	38,135.037	38,147.498
L_{82}	40,460.214	40,469.309	28,937.143	28,961.850	41,479.016	41,504.773	43,405.717	43,440.420
L_{80}	45,494.532	45,516.185	32,537.699	32,576.859	46,640.114	46,683.552	48,806.551	48,861.767
L_{78}	50,656.343	50,687.008	36,229.418	36,280.652	51,931.890	51,989.501	54,344.129	54,416.229
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	65,858.507	65,944.794
L_{72}	66,975.459	66,990.551	47,900.875	47,958.705	68,661.942	68,719.204	71,851.283	71,929.528
L_{70}	72,718.941	70,875.766	52,008.574	50,741.645	74,550.044	72,705.949	78,012.892	76,103.018

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 7: Mdl 2 output vs. LED chip lifetime.

Lifetime maintenance	1500 mA/57.3 °C Target	1500 mA/57.3 °C Output	1500 mA/87.5 °C Target	1500 mA/87.5 °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	3818.217	2945.860	2783.437	4222.648	4006.339	4418.790	4289.884
L_{96}	8322.795	7889.633	5952.463	5683.255	8532.367	8159.987	8928.695	8614.042
L_{94}	12,615.171	12,352.778	9022.367	8862.082	12,932.822	12,713.281	13,533.553	13,354.248
L_{92}	16,999.856	17,012.808	12,158.298	12,181.137	17,427.922	17,467.437	18,237.447	18,303.561
L_{90}	21,480.923	21,690.503	15,363.154	15,512.773	22,021.820	22,239.611	23,044.732	23,271.636
L_{88}	26,062.690	26,289.418	18,640.035	18,788.298	26,718.959	26,931.417	27,960.055	28,156.041
L_{86}	30,749.799	30,844.624	21,992.257	22,032.690	31,524.090	31,578.631	32,988.384	32,994.020
L_{84}	35,547.200	35,507.528	25,423.360	25,353.793	36,442.292	36,335.713	38,135.037	37,946.382
L_{82}	40,460.214	40,447.607	28,937.143	28,872.310	41,479.016	41,375.573	43,405.717	43,193.132
L_{80}	45,494.532	45,721.041	32,537.699	32,628.263	46,640.114	46,755.556	48,806.551	48,793.963
L_{78}	50,656.343	51,203.237	36,229.418	36,532.892	51,931.890	52,348.469	54,344.129	54,616.448
L_{76}	55,952.231	56,634.208	40,017.038	40,401.028	57,361.111	57,889.108	60,025.557	60,384.558
L_{74}	61,389.370	61,728.828	43,905.687	44,029.615	62,935.171	63,086.614	65,858.507	65,795.451
L_{72}	66,975.459	66,269.116	47,900.875	47,263.386	68,661.942	67,718.591	71,851.283	70,617.542
L_{70}	72,718.941	70,138.976	52,008.574	50,019.641	74,550.044	71,666.623	78,012.892	73,852.756

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

Lifetime maintenance	1500 mA/57.3°C Target	1500 mA/57.3°C Output	1500 mA/87.5°C Target	1500 mA/87.5°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	4047.894	2945.860	2858.584	4222.648	4114.390	4418.790	4284.867
L_{96}	8322.795	7507.493	5952.463	5346.754	8532.367	7680.967	8928.695	8029.431
L_{94}	12,615.171	11,950.713	9022.367	8541.899	12,932.822	12,260.853	13,533.553	12,837.402
L_{92}	16,999.856	17,031.934	12,158.298	12,194.742	17,427.922	17,496.592	18,237.447	18,332.747
L_{90}	21,480.923	22,156.159	15,363.154	15,876.080	22,021.820	22,772.734	23,044.732	23,867.975
L_{88}	26,062.690	26,839.843	18,640.035	19,236.212	26,718.959	27,587.647	27,960.055	28,914.388
L_{86}	30,749.799	31,032.743	21,992.257	22,236.295	31,524.090	31,885.171	32,988.384	33,410.210
L_{84}	35,547.200	35,109.318	25,423.360	25,142.358	36,442.292	36,046.019	38,135.037	37,751.710
L_{82}	40,460.214	39,600.678	28,937.143	28,333.281	41,479.016	40,612.717	43,405.717	42,505.249
L_{80}	45,494.532	44,858.880	32,537.699	32,061.290	46,640.114	45,946.632	48,806.551	48,049.213
L_{78}	50,656.343	50,792.038	36,229.418	36,263.670	51,931.890	51,958.486	54,344.129	54,293.395
L_{76}	55,952.231	56,844.226	40,017.038	40,548.521	57,361.111	58,088.014	60,025.557	60,657.874
L_{74}	61,389.370	62,304.681	43,905.687	44,413.736	62,935.171	63,617.060	65,858.507	66,398.119
L_{72}	66,975.459	66,698.688	47,900.875	47,523.797	68,661.942	68,065.879	71,851.283	71,016.535
L_{70}	72,718.941	69,929.003	52,008.574	49,810.105	74,550.044	71,336.352	78,012.892	73,099.388

Table 9: Lifetime prediction (L_{70}).

Model type	Lifetime (hrs.)
Reference	76,216.842
Exponential function	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 105.50°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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