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TRIZ Metodolojisi Kullanılarak LED'lerde Ömür Belirleme Süresinin Kısaltılması

Shortening the Life Determination Period in LEDs Using TRIZ Methodology

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ÖZET

Bu çalışma, yenilikçi bir çözüm olarak TRIZ (Yaratıcı Problem Çözme Teorisi) metodolojisini kullanarak LED yaşlanması ve kullanım ömrü tahmini konusundaki basit optimizasyon yaklaşımlarının ötesine geçmektedir. TRIZ çerçevesindeki temel teknik çelişkiye göre, yüksek hassasiyetli LED ömür tahmini uzun süreli yaşlanma testlerini gerektirir. Bu denli uzun testlerin yapılması, LED'in pazara sunulma süresini geciktirir, zaman kaybına yol açar ve verimliliği düşürür. Doğruluk için gereken uzun test süreleri ile hızlı pazar girişi için ihtiyaç duyulan kısa zaman dilimleri arasındaki çatışmadan, buna karşılık gelen fiziksel bir çelişki doğar. Bu çelişkileri ele almak için TRIZ'in ayırma ilkelerinden yararlanılır. Zamansal ayırma yaklaşımı kullanılarak hızlandırılmış yaşlanma testleri gerçekleştirilir. Bu süreci, mekânsal ayırma yaklaşımıyla farklı çevresel ve operasyonel koşullar altında yürütülen eşzamanlı testler takip eder. Ayrıca, LED yaşlanma süreçlerinin verimliliğini artırmak amacıyla: Bölütleme, Ayırma, Ön İşlem, Tersine Çevirme, Dinamizm, Periyodik İşlem, Ekipman, Ucuz ve Kısa Ömürlü Nesneler, Parametre Değişimi ve Kompozit Malzemeler gibi TRIZ'in "40 Buluş İlkesi"nden yararlanılır. Böylece çalışma, TM-21 ve LM-80 standartları çerçevesinde LED'lerin sıcaklığa bağlı yaşlanma davranışını ve kullanım ömrü tahminini analiz eder. TRIZ metodolojisi, bu sistematik problem çözme yaklaşımı sayesinde doğruluk ile test süresi arasındaki farkı önemli ölçüde azaltır. Böylece, en doğru LED ömür tahmini maksimum doğruluk ve minimum test süresiyle elde edilebilir.

Anahtar Kelimeler: TRIZ, LED, optimizasyon, aydınlatma, verimlilik

ABSTRACT

This study moves beyond simple optimization approaches regarding LED aging and service life prediction by employing the TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) methodology as an innovative solution. According to the fundamental technical paradox within the TRIZ framework, high-precision LED lifespan prediction requires long-duration aging tests. Conducting such lengthy tests delays the LED's time-to-market, results in wasted time, and reduces efficiency. A corresponding physical paradox arises from the conflict between the long testing periods required for accuracy and the short timeframes needed for rapid market entry. To address these paradoxes, TRIZ's separation principles are utilized. Accelerated aging tests are conducted using a temporal separation approach. This process is followed by simultaneous tests performed under varying environmental and operational conditions, employing a spatial separation approach. Furthermore, to enhance the efficiency of LED aging processes, principles from TRIZ's "40 Inventive Principles" such as Segmentation, Separation, Preliminary Action, Inversion, Dynamism, Periodic Action, Equipment, Cheap Short-Lived Objects, Parameter Change, and Composite Materials are applied. Thus, the study analyzes the temperature-dependent aging behavior and service life prediction of LEDs within the framework of TM-21 and LM-80 standards. Through this systematic problem-solving approach, the TRIZ methodology significantly narrows the gap between accuracy and testing duration. Thus, the most accurate LED lifespan estimate can be obtained with maximum accuracy and minimum test duration.

Keywords: TRIZ, LED, optimization, lighting, efficiency

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1. Introduction

Predicting the lifespan and lumen retention (L_{70}/L_{90}) of LED lighting fixtures requires extensive aging tests of 6,000 to 10,000 hours, as required by international LM-80/TM-21 standards. This leads to high costs in product development and time-to-market delays. The aim of this study is to systematically resolve the technical contradiction between accurately predicting the aging behavior of LEDs depending on temperature and operating conditions and shortening test times using the TRIZ methodology. The main objective of this study is to significantly shorten test time while maintaining LM-80/TM-21 accuracy thanks to the spatio-temporal decomposition principles of TRIZ.

While studies in the literature mostly rely on classical extrapolation or statistical estimation, this study offers three unique dimensions:

(1) It utilizes holistic models of real-time discrepancy with the time- and space-based decomposition principles of TRIZ.

(2) It enables the transfer of LM-80 data to TM-21 mathematics using the principles of Segmentation (Principle 1), Separation (Principle 2), Preventive Countermeasures (Principle 10), Doing the Opposite (Principle 13), Dynamism (Principle 15), Periodic Action (Principle 19), Equipment (Principle 24), Cheap and Short-Lived Items (Principle 27), Parameter Change (Principle 35), Composite Materials (Principle 40).

(3) It provides experimental and mathematical improvements with a hybrid approach that complies with standards.

From an economic and commercial perspective, it shortens the R&D and quality control times of manufacturers, increases the speed of product-to-market, and directly saves money by minimizing energy and laboratory costs.

While existing studies on LED aging and life estimation utilize an optimization approach, this study employs the TRIZ methodology, a method that goes beyond optimization. In this context, the fundamental technical contradiction encountered with the TRIZ approach in LED aging and life estimation is the need for long-term aging tests to accurately predict LED lifespan (Altshuller, 1984; Atiç, 2016; Atiç and İzgi, 2024). However, these tests negatively impact time and efficiency by extending the time to market for the manufactured product. Similarly, a physical contradiction arises: since it is desired that the manufactured LED be commercially viable by quickly bringing it to market, a long testing period is undesirable in terms of accuracy in LED life estimation (Cengiz, 2026). To overcome these contradictions, the decomposition principles of TRIZ are used. While accelerated aging tests are applied using the time decomposition approach in TRIZ, simultaneous tests can be performed under different environmental and operating conditions using the spatial decomposition approach. Furthermore, the principles of pre-comparison, consistency variation, and acceleration, which are among the 40 innovation principles of TRIZ, can be used to make LED aging processes more efficient. Therefore, within the framework of TM-21 and LM-80 standards, the temperature-dependent aging behavior and lifespan prediction processes of LEDs are analyzed. Thanks to the systematic solution approach offered by the TRIZ methodology, the differences between accuracy and test time are significantly reduced (Illuminating Engineering Society, 2021).

2. Identifying problems in LED lifespan prediction

Processes for predicting lifespan in LED technology can be directly and systematically modeled using the concepts of technical and physical contradictions that form the basis of the TRIZ (Theory of Inventive Problem Solving) methodology (Ekmekçi and Nebati, 2019). Long testing periods, statistical uncertainties, and measurement difficulties encountered in industrial applications are fundamental contradiction structures that arise when improving one parameter of the system leads to the deterioration of another, or when a single parameter simultaneously meets two opposed requirements. Instead of glossing over these contradictions, TRIZ provides the opportunity to develop innovative approaches that address the source of the contradictions and transform the fundamental functionality of the system. In this context, technical contradictions manifest themselves when an effort to improve one attribute of the system leads to a measurable deterioration in another attribute. For example, minimizing product development and validation test times is essential for survival in a highly competitive market. Shortening the test time leads to a significant decrease in the statistical reliability and accuracy of lifespan prediction. Similarly, the goal is to determine the junction temperature, the most critical physical quantity determining the lifespan of an LED, with high accuracy and without error. This leads to an increase in the complexity and cost of thermal modeling, numerical simulations, and physical test setups (Lee et al., 2018). This cost increase is undesirable.

Physical contradictions arise from the necessity for a single component or parameter within the system to simultaneously embody two opposing physical states or demands. LED testing processes provide the most typical example of this phenomenon: while a long test duration is a necessity to obtain statistically acceptable and reliable data under the LM-80 standard, it is equally essential to keep this duration as short as possible due to market speed dynamics and production planning. A similar physical contradiction arises when temperature measurement is required at the junction region. For accurate and direct measurement, this critical region is expected to be mechanically open, accessible, and suitable for probe placement, while the electrical stability, thermal management, and environmental protection requirements of the LED necessitate that this region be closed, isolated, and protected (Cengiz and Cengiz, 2018).

Defining these problems within the framework of the TRIZ paradox approach prevents some manufacturers in the sector from resorting to empirical and erroneous estimation methods that disregard standards. Instead, TRIZ enables the development of realistic, measurable, and holistic solution strategies consistent with the overall operation of the system. To overcome this paradox, TRIZ uses the "Time Dimension Separation" principle to address this fundamental inconsistency regarding test duration. In this approach, critical early-stage data is collected quickly by initially keeping the physical test duration short. Then, this paradox is transferred to a virtual environment using statistical learning models, mechanical decay kinetics, or AI-powered extrapolation algorithms, and long-term performance trends are predicted. In this way, while remaining within the accuracy limits of the physical test, the market's demand for speed is also met. Thus, neither accuracy nor time is compromised, and the solution is implemented at the optimal level (Van Erp et al., 2019).

In short, lifespan estimation in LED technology faces long testing periods (LM-80 measurements require at least 6000 hours, which delays market launch), accuracy and reliability issues (estimating long-term lifespan from short-term tests creates statistical uncertainties; the TM 21 standard does not accept estimates exceeding six times the measurement time), the complex influence of temperature and other parameters (thermal modeling and different statistical approaches are necessary because the junction temperature cannot be measured directly), and industrial inconsistencies (some manufacturers undermine consumer confidence by declaring lifespan values without completing tests or using faulty methods. The inability of these companies to properly conduct tests is considered a lack of standardization and a reliability problem in the system. This is treated as a system failure in the TRIZ approach). These problems encountered in lifespan estimation for LED technology can be modeled with TRIZ's concepts of "technical inconsistency" and "physical inconsistency" (Hulett et al., 2020; Illuminating Engineering Society, 2021).

3. TRIZ contradiction analysis for LED lifespan determination

- Among the improved aspects, the comprehensiveness of the test for different temperature, current, etc., conditions represents a key improvement. On the negative side, the discrepancy between test cost and the complexity of the physical testing process stands out as a challenge to overcome. This technical contradiction, which necessitates the inclusion of different temperature, current, and environmental variables in LED technology testing processes, leads to increased production costs. While multivariate and comprehensive test protocols offer more realistic and reliable LED lifespan predictions closer to actual operating conditions, they also increase equipment requirements, energy consumption, labor, and data processing challenges. The TRIZ methodology does not accept these conflicting demands as a compromise. Instead, TRIZ develops an innovative solution that provides comprehensiveness without increasing cost and complexity.
- In the same system, the conflicting demands necessitate a long test duration. This is because a long time is required to capture the correct decay curve and make reliable predictions. LED technology only produces an accurate decay curve through lengthy physical trials. However, for the product to be usable, marketable, and competitive in the market, the test duration must be completed as quickly as possible. This physical contradiction leads to the paradox of requiring both long and short test durations. The TRIZ method proposes decomposition principles to reconcile these conflicting demands. For example, it aims to resolve the contradiction by separating the test in time (with acceleration) or space (with parallel tests under different conditions).
- The TRIZ method, with its Ideal Final Result (IFR) approach, defines the ultimate goal to be achieved in LED lifespan prediction. According to IFR, the system should not require any physical testing, relying solely on mathematical models based on manufacturing parameters and material properties, and should instantly determine lifespan values with complete accuracy without needing any additional time. This summarizes TRIZ's vision for ideality. In other words, the existing negative aspects regarding the discrepancies between time, cost, and accuracy in the final target product should be eliminated.

- The resource analysis for this study encompasses time resources, information resources, space resources, functional resources, and system resources. Using the TRIZ methodology, existing and potentially usable assets are systematically categorized. As a time resource, decay data generated according to the LM-80 standard is collected. As an information resource, pre-existing predictive inputs such as the manufacturer's past product data, material characteristics, and thermal simulation results, if available, are considered. Space resource information is generated through temperature measurements taken from different regions of the LED module, such as the cathode, anode, and casing. This reveals the advantage of the LED module's physical layout. Functional resources include accelerated aging tests with high-temperature and current applications. This provides the potential to shorten the physical duration. In terms of system resources, existing industrial infrastructure resources such as the computational tools and extrapolation algorithms offered by the TM-21-related standards are utilized. The effective integration of these resources offers strategic advantages with high efficiency in overcoming the discrepancies between test time, accuracy, and cost (Hulett et al., 2020; Illuminating Engineering Society, 2020; Illuminating Engineering Society, 2021).

4. Solution proposals based on TRIZ invention principles

To address the issues highlighted in this study, the following TRIZ principles are proposed (Altshuller, 1984; Ekmekçi and Nebati, 2019):

1. TRIZ Segmentation Principle 1 suggests breaking down complex test components into smaller, manageable stages. This capability allows illumination time tests to be performed in two modules: short-duration accelerated tests and long-duration real-use tests. Accelerated tests identify early failures, while long-duration tests reveal the actual use performance of the product. The results obtained are more accurately predicted in terms of product efficiency and service life; thus, accuracy is maintained while reducing test time and cost.
2. TRIZ Extraction Principle 2 suggests testing aging-causing factors such as temperature and current separately, rather than together. This allows the effect of temperature and speed on product life, as well as the activation energy of each parameter, to be determined independently. By combining the results, the actual service life of the product is more accurately predicted, and failure units are analyzed more clearly.
3. TRIZ's Preliminary Anti-action Principle 10 recommends proactive measures to mitigate potential future problems before they arise. With this approach, temperature sensors are integrated into LED chips during the manufacturing process, allowing for continuous monitoring of the operating system. The data is analyzed in real-time to identify potential performance loss and premature failure risks caused by excessive temperature fluctuations. This allows for the prediction of the product's remaining lifespan, the planning of necessary maintenance, and an extended lifespan of the preventative system in place to address potential failures before they occur.
4. TRIZ's "Do it in Reverse" Principle 13 suggests solving the problem from a different perspective by applying the reverse of the traditional method. The classic approach to LEDs is to conduct long-term aging tests to determine the product's lifespan. According to this principle, instead of long-term life tests, the physical mechanisms causing degradation are directly modeled. For example, by developing physics-based models that simulate processes such as lattice defects in semiconductor structures, interfacial oxidation, thermal fatigue, and material aging, the product's lifespan can be predicted in advance. This allows for faster, lower-cost, and scientifically based reliability analyses without the need for long testing periods.
5. TRIZ's "Dynamicity" Principle 15 suggests changing the system or operating conditions according to need, rather than keeping them constant. In this context, temperature and current values in LED life tests are dynamically changed according to specific scenarios instead of being applied constantly throughout the test. This yields accelerated aging curves representing different operating conditions, and these data are adapted to dynamic reliability models to predict the actual lifespan of the product more accurately and quickly.
6. TRIZ's Periodic Action Principle 19 recommends using periodic processes instead of continuous, uninterrupted operations. In line with this approach, performance data in LED lifespan tests is measured at specific intervals rather than continuously monitored. This reduces the burden of unnecessary data collection and analysis, decreases the number of measurements, and significantly reduces total test time and cost. Periodically obtained data reliably reveal the aging tendency of the product, enabling a more efficient testing process.
7. TRIZ's Mediator Principle 24 suggests using an intermediary element or method instead of directly performing the interaction between two systems or processes. Since directly measuring junction temperature in LED reliability tests is difficult and costly, thermal impedance measurements are performed instead. These measurements are then converted to junction temperature using pre-established calibration functions or

mathematical models. Thus, critical temperature information is obtained accurately without requiring direct measurement; the testing process becomes more practical, faster, and economical.

8. TRIZ's Cheap Short-Living Objects Principle 27 suggests processing on low-cost and potentially expendable samples instead of directly using expensive or final products. In this context, destructive lifetime and durability tests are performed on low-cost test (version) chips in LED reliability studies. Failure and aging data obtained from these tests are analyzed to make predictions about the lifespan and reliability of the final product with the same manufacturing process. This reduces testing costs while preventing damage to the main products.
9. TRIZ's Parameter Change Principle 35 suggests replacing the primary parameter used to assess the problem with a more suitable or sensitive one. In LED reliability analyses, instead of monitoring aging solely through temperature, spectral changes in luminous flux (changes in color temperature, wavelength shifts, or red/blue light ratio) can be used as indicators of premature degradation. Since these spectral changes can reveal material aging and performance loss in the LED before the temperature increase, they allow for earlier and more accurate prediction of product life. Thus, failures can be detected before they become apparent, and reliability assessments can be performed more effectively.
10. TRIZ's Composite Materials Principle 40 suggests combining materials with different properties to improve system performance. In LED reliability testing, using composite materials with high thermal conductivity (e.g., ceramic-based substrates, metal-core PCBs, or graphene-doped materials) can make the temperature distribution within the LED more homogeneous. This reduces the formation of local hot spots, lowers variability in test results, and makes thermal behavior more predictable. As a result, the reliability model can be built more simply and accurately, and product life cycle predictions become more reliable.

Figure 1 shows the block diagram of the proposed TRIZ principles.

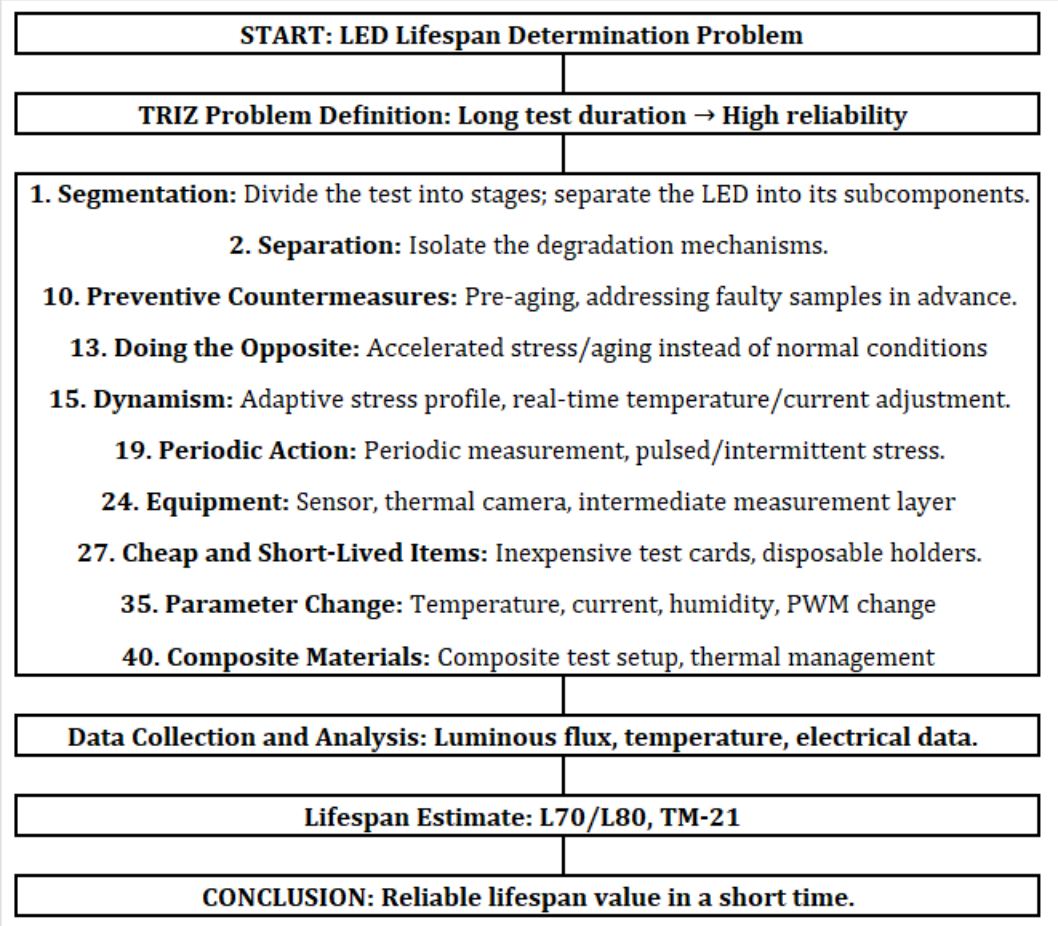


Figure 1. The block diagram of the proposed TRIZ principles.

5. TRIZ S-Curve and Supersystem Laws

LED lifecycle prediction systems are still in their infancy, and efficiency can be increased through accelerated testing and AI-powered data analysis. In the future, this function will be embedded in smart lighting systems (supersystems) (Tekin and Efe, 2025). Each luminaire will be able to calculate its own lifespan based on its operating history. This is consistent with TRIZ's "Law of Transition to a Supersystem." The TRIZ methodology assumes that all technological and engineering systems evolve not randomly, but according to specific objective

laws. These Laws of Evolution of Technical Systems, defined by Genrich Altshuller, are used to predict the direction of innovation and resolve engineering contradictions. Two of the most fundamental tools of these laws are the S-Curve and the Law of Transition to a Super-system (Altschuller, 1984; Shirwaiker and Kremer, 2008).

The S-Curve represents the lifecycle of technical systems. It is a logistic growth curve showing the development, performance, and efficiency of a technical system over time. Just like biological organisms, every technological product or system is born, grows, matures, and ultimately completes its lifecycle. The S-curve typically consists of four main stages. Figure 2 shows the typical S-curve for an incandescent lamp.

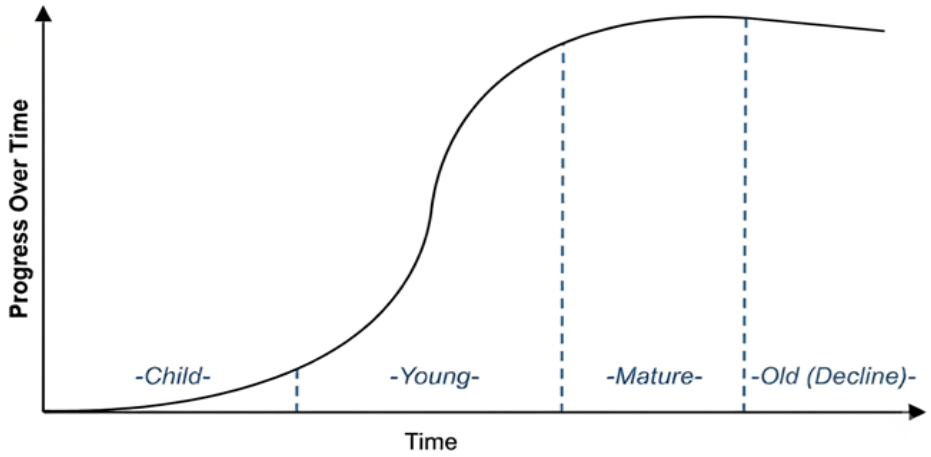


Figure 2. Typical S-Curve of an incandescent lamp.

According to TRIZ's Law of Transition to Supersystems, the evolution of lighting progresses from an inefficient piece of wire (incandescent bulb) to a fluorescent bulb, then to a highly efficient semiconductor chip (LED), and finally from a standalone device to a smart component of a massive supersystem that forms the digital infrastructure of a city. This continuous development is a vivid example of TRIZ's laws of evolution (Canbulut and Demirtaş, 2022; Savransky, 2020). TRIZ's Law of Transition to Supersystems states that when a technology reaches its limits, development can no longer continue solely through improvements to its own components. Instead, it must transform into part of a larger system by gaining new functionalities. Lighting technologies are one of the most prominent examples of this transformation. When LED technology reaches maturity in terms of light efficiency, energy consumption, and lifespan, it is no longer sufficient to improve the lighting element as a more efficient light source. At this point, the lighting fixture ceases to be a standalone product and becomes a component of more comprehensive and interactive systems. Therefore, technological development not only improves the performance of a single device but continues by integrating different technologies into that device. Figure 3 shows the current S-Curve for incandescent lamps and the emerging LED technology.

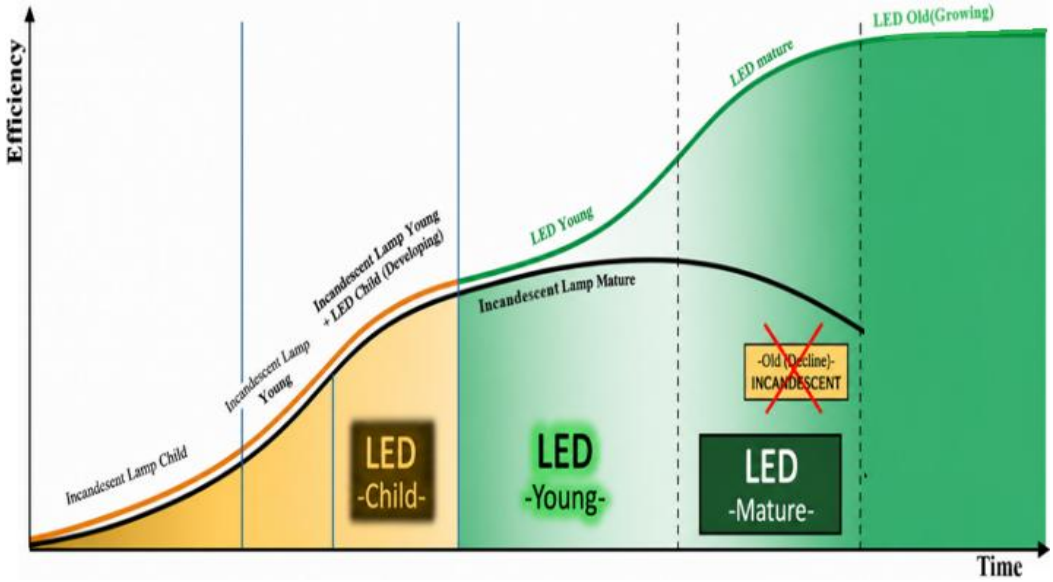


Figure 3. Current S-Curve for incandescent lamps and evolving LED technology

The first stage of this transformation was the transition from a monosystem to a polysystem, i.e., the process of heterogeneous integration. Instead of simply providing lighting, traditional LED luminaires have been integrated

with various technologies such as motion sensors, daylight sensors (LDRs), presence sensors, and local photovoltaic (PV) panels. Thus, the lighting system has transformed from a passive device that only produces light into an intelligent system capable of sensing its surroundings, making decisions based on environmental conditions, and, in some applications, generating a portion of its own energy. This integration has reduced unnecessary energy consumption, increased user comfort, and significantly improved the overall efficiency of the system. Figure 4 shows the S-Curve with intelligent lighting included in the Super system.

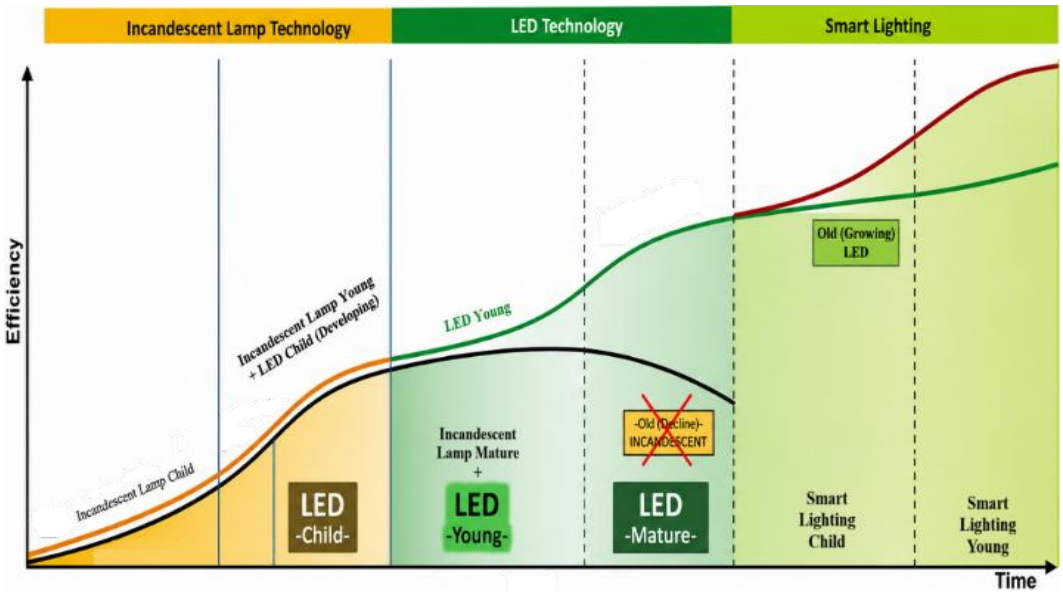


Figure 4. Smart lighting S-Curve integrated into the Super system

In the second phase of development, lighting systems have become an integral part of Smart Grid and Smart City infrastructures, truly integrated into the Super system. Today, modern street lighting and industrial lighting systems not only illuminate the environment but also function as multifunctional platforms that collect data, communicate, and support city infrastructure. Cameras, air quality and environmental sensors, noise meters, 5G communication equipment, electric vehicle charging units, and various IoT components are integrated into these systems. These smart luminaires, connected to a central control system, can dynamically adjust light levels based on traffic density, pedestrian movement, or ambient light, optimize energy use, and automatically report malfunctions to the control center. Thus, the lighting system has ceased to be merely an infrastructure element that provides light and has become a multifunctional super-system component that generates data, manages energy, and contributes to city management. This transformation is considered one of the most concrete applications of TRIZ's Super System Transition Act in lighting technologies.

When examining the development of lighting technologies, it is evident that this evolution is not only about producing more efficient light sources but also entails a functional transformation at the system level. First-generation incandescent bulbs relied on an inefficient technology that produced light by passing an electric current through a high-resistance filament, but converted most of the consumed energy into heat. Therefore, incandescent bulbs were considered independent, passive devices whose primary function was to illuminate the environment. Later, LED technology emerged; its semiconductor-based operation offered much higher energy efficiency, longer lifespan, and lower maintenance needs, marking a major leap in lighting. At this stage, the lighting element transformed from an inefficient filament to a highly efficient electronic chip, providing significant gains in energy performance.

However, technological development did not stop there. With the maturation of LED technology, improvements aimed solely at increasing light production efficiency began to yield increasingly diminishing returns, and lighting systems entered a new transformation process. In this process, luminaires, equipped with sensors, communication modules, cameras, environmental measuring devices, and AI-powered control systems, have become an active component of Smart City and IoT infrastructures. Today, a modern streetlight pole not only produces light but can also monitor traffic density, measure air quality, optimize energy consumption, report malfunctions to a central system, and continuously exchange data with other city infrastructures.

According to TRIZ's Law on Transition to Supersystems, the evolution of lighting can be summarized as a transformation from an inefficient piece of wire (incandescent bulb, Figure 2) to a highly efficient semiconductor chip (LED, Figure 3), and from a standalone device to a smart component of a future supersystem forming the city's digital infrastructure (Smart lighting, Figure 3). In other words, today's lighting systems are no longer just light-providing equipment; they are multifunctional nodes supporting energy management, data communication,

environmental monitoring, security, and smart city applications. This transformation, consistent with TRIZ's Law of Transition to Supersystems, demonstrates that technological development is progressing from a device-centric approach to system-centric and networked structures.

6. Solution Strategies

This hybrid Acceleration Method combines the results of short-term (e.g., 1000 hours) high-temperature and high-current stress acceleration tests with the results of long-term low-stress tests to overcome the time-accuracy discrepancy in LED lifetime testing. The obtained data are evaluated together through the Arrhenius model (Equation 1), which explains the effect of temperature on the degradation rate, and the exponential decay model, which describes the decrease in luminous flux over time (Illuminating Engineering Society, 2020; Illuminating Engineering Society, 2021).

$$k = A.e^{\frac{Ea}{RT}} \qquad (1)$$

k: Reaction rate constant
A: Frequency factor or pre-exponential factor (number and orientation of collisions)
E_a: Activation energy (minimum energy required to start the reaction)
R: Universal gas constant (*8.314 J/mol.K*)
T: Absolute temperature in Kelvin

$$Q_{(t)} = Q_0.e^{-\propto t} \qquad (2)$$

The L_{70} lifetime, calculated using the exponential decay model of luminous flux, represents the point at which the luminous flux of a lighting source drops to 70% of its initial value ($0{,}70.\Phi_o$). Within the industry standard IES TM-21, this calculation is performed using the logarithmic transformation of the exponential model.
In the first step, to derive the model and calculate the L_{70} lifetime, $0{,}70.\Phi_o$ is substituted for $\Phi(t)$ in the basic exponential decay equation. The Φ_o values are then simplified from both sides.

$$0.70.\Phi_o = \Phi_o .e^{-\propto.L_{70}} \qquad (3)$$

The natural logarithm of both sides of the equality is taken.

$$\ln(0.70) = -\propto. L_{70} \qquad (4)$$

$$-0.3567 = -\propto. L_{70} \qquad (5)$$

$$L_{70} = \frac{0.3567}{\propto} \qquad (6)$$

The next step involves the L_{70} calculation process. In lighting engineering, the L_{70} lifespan is calculated using IES LM-80 test data in the following steps:

- Data Collection: The luminaire or LED is operated at a specific temperature (e.g., 55°C or 85°C) for at least 6000 hours, and the luminous flux is measured at regular intervals.
- Regression Analysis: The degradation coefficient (α) and the corrected initial constant (B) are derived by applying the least squares method to the obtained time and luminous flux data.
- Life Projection: The obtained (α) value is converted using the above formula to determine at what hour the luminaire will degrade to 70% performance.

The L_{70} lifespan capacities of three different LED drivers with different degradation rates (α) (high (α_1=5 10^{-6}), medium (α_2=7.1 10^{-6}), and low quality (α_3=12 10^{-6})) are compared. Substituting these α values into Equation 6 yields an L_{70} lifespan estimate of 71.340 hours for α_1. Similarly, the L_{70} lifespan estimate for α_2 is calculated as 50.239 hours, and for α_3 as 29.725 hours.
In this way, accelerated degradation data from high-stress testing is transferred to normal operating conditions using the Arrhenius equation, and long-term lifespan estimation is performed using an exponential model. This allows for a similarly accurate prediction with a total test period of approximately 3000 hours, instead of the traditional 6000- 9000-hour test periods. Thus, the total test time is reduced by more than 50%, speed to market is increased, resource consumption and costs are reduced, and a scientifically based solution compliant with LM-80 / TM-21 standards is provided (Illuminating Engineering Society, 2020; Illuminating Engineering Society, 2021).

This Virtual LED Model (Digital Twin) creates a physics-based degradation simulator using the manufacturing parameters (epitaxy quality, junction temperature, reflective coating, etc.) of each LED batch. After calibration with real tests, this model can instantly and with high accuracy predict the lifespan of new batches without any physical testing, simply by entering manufacturing data; thus, testing time, cost, and resource consumption are radically reduced. This Early Warning Indicators approach envisions the use of hardware that monitors junction temperature and forward voltage in real-time as an alternative to traditional long-term luminous flux measurements for predicting LED lifespan. Since small deviations in forward voltage reflect the intrinsic degradation processes of the LED much earlier than the decrease in luminous flux, monitoring these electrical parameters allows for early and reliable warnings about lifespan (Cengiz, 2020; Cengiz, 2022; Tuna and Efe, 2023). Thus, it becomes possible to achieve predictions similar to or faster than thousands of hours of photometric testing with short-term electrical characterization tests. This significantly reduces testing time and cost.

The Flexibility approach in these standards introduces a new interpretation framework called “enhanced TM 21+” by relaxing the strict limit of “maximum 6 times the test duration” imposed by the existing TM-21 standard for life extrapolation, using wider confidence intervals and advanced statistical extrapolation models. This allows for much longer-term life predictions (e.g., 50000 hours and above) than permitted by the standard, using the same physical test data. This provides LED manufacturers with the flexibility to certify longer-lasting products without requiring additional testing time or cost, thus gaining a competitive advantage.

This industrial audit mechanism, applying TRIZ’s “pre-contrast” principle, mandates that independent testing laboratories record LM-80 test results using blockchain technology. Blockchain ensures transparent, immutable, and time-stamped data storage, preventing manufacturers or laboratories from manipulating results or making false statements. This minimizes reliability and verifiability issues in the industry, while making compliance audits more effective and independent.

7. Discussion and Conclusion

First, the analysis reveals that the most fundamental contradiction in LED lifespan prediction is the dilemma between accuracy and time. This contradiction can be overcome by TRIZ's physical decomposition principles, accelerating test processes over time and dividing them into parallel tests under spatially varying stress conditions, and employing advanced simulation techniques such as virtual modeling (digital twin).

The analysis then explains how three innovative methods (hybrid acceleration testing, a digital twin-based degradation simulator, and electrical indicators providing early warning) can transform the existing LM-80/TM-21 standard framework. This transformation significantly reduces physical test times while increasing the statistical reliability and accuracy of predictions. This achieves a balance consistent with TRIZ's goal of "correcting the deteriorating parameter while maintaining the improved parameter."

Finally, it is shown that these technical solutions alone are insufficient and need to be supported by industrial regulations and standard updates. For example, blockchain-based independent audit mechanisms and flexible predictive (extrapolation) approaches like advanced TM-21+ enhance the transparency and reliability of the system, creating a mutual benefit for all stakeholders, including producers and consumers. Ultimately, in line with TRIZ's laws of technological evolution, these innovations are expected to be integrated into smart lighting ecosystems (Internet of Things, smart city lighting, etc.) in the near future. This indicates that LED lifecycle management will transform from a passive testing process to an active and predictive digital service platform.

8. Results

In the LED lighting industry, the L_{70} lifespan calculation process is undergoing a significant transformation from traditional long-term photometric testing methods to data-driven and physics-based simulation approaches. This study compares L_{70} lifespan predictions for LED drivers of different quality levels using the decay coefficient (α) obtained through regression analysis based on IES LM-80 test data. Lifespan values of approximately 71.340, 50.239, and 29.725 hours were calculated for high (α_1=5 10^{-6}), medium (α_2=7,1 10^{-6}), and low-quality (α_3=12 10^{-6}) drivers, respectively; these results clearly demonstrate the decisive effect of the decay rate on lifespan.

Transferring data from accelerated stress tests to normal operating conditions via the Arrhenius equation and performing lifespan projection with an exponential decay model shortens the testing time. The total testing time is reduced by more than 50%, as similarly accurate predictions can be obtained with approximately 3000 hours of total testing time instead of the traditional 6000-9000 hours. This advantage also increases time to market and reduces resource consumption and costs. The entire process provides a scientifically based and compliant solution in accordance with LM-80/TM-21 standards.

In addition, the Virtual LED Model (Digital Twin) approach creates a physics-based degradation simulator using the production parameters of each LED batch (epitaxy quality, junction temperature, reflective coating, etc.) and, after calibration with real tests, can instantly and accurately predict the lifespan of new batches without performing

any physical tests. This significantly reduces testing time, cost, and resource consumption. Furthermore, the Early Warning Indicators approach enables real-time monitoring of electrical parameters such as junction temperature and forward voltage as an alternative to traditional long-term luminous flux measurements.

Since small deviations in transmission voltage reflect the intrinsic degradation processes of the LED long before a decrease in luminous flux, monitoring these parameters provides early and reliable warnings about lifespan. Therefore, short-term electrical characterization tests can provide similar or faster predictions compared to thousands of hours of photometric testing.

Significant flexibility is also provided in terms of standards. The new interpretation framework, "Enhanced TM-21+", relaxes the strict limit of "maximum 6 times the test duration" imposed by the existing TM-21 standard for lifespan predictions, using wider confidence intervals and improved statistical prediction models. This approach allows for much longer lifespan predictions (e.g., 50.000 hours and above) than permitted by the standard with the same physical test data. This approach gives LED manufacturers the flexibility to certify longer-lasting products without additional testing time or cost, providing them with a competitive advantage.

The industrial audit mechanism, developed in accordance with TRIZ's "preliminary comparison" principle, mandates that independent testing laboratories record LM-80 test results using blockchain technology. Blockchain technology prevents manufacturers or laboratories from manipulating results or making false statements by providing transparent, immutable, and time-stamped data storage. This minimizes reliability and verifiability issues in the industry, making compliance audits more effective and independent. When all these developments are considered together, the TRIZ method can provide a comprehensive improvement in speed, accuracy, cost-effectiveness, and reliability in LED lifespan testing processes, offering a sustainable, science-based roadmap for the LED manufacturing sector.

Ethics Committee Approval and Conflict of Interest Statement

No ethics committee approval is required for this article.

Conflict of Interest Statement

There is no conflict of interest with any person/institution regarding this article.

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This article is a single-authored work.

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