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DIGITAL-TWIN-ENABLED SELF-HEALING CONTROL FOR RESILIENT SMART STREET LIGHTING SYSTEMS

Plamen Stanchev[1,*], Nikolay Hinov[2], Plamen Nakov[2]

[1] Technical University of Sofia, Department of Intelligent Technology in the Industry, 8, Kliment Ohridsky blvd. Sofia, Bulgaria
[2] Technical University of Sofia, Department of Computer Systems, 8, Kliment Ohridsky blvd. Sofia, Bulgaria

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**Corresponding author: p.stanchev@tu-sofia*

Abstract
Smart street-lighting systems are increasingly expected to combine energy-efficient operation with resilience to luminaire degradation and unexpected failures. This study proposes a Digital-Twin-enabled self-healing control framework for maintaining lighting performance under abnormal operating conditions. The developed Digital Twin incorporates the measured I(C,γ) photometric distribution of a commercial Philips RoadFlair Gen2 LED luminaire and evaluates maintained horizontal illuminance using an EN 13201-oriented calculation framework. A representative single-sided installation is investigated under healthy operation, complete single-luminaire failure, simultaneous multiple failures, and progressive luminous-output degradation. Under normal operation at 60% luminaire output, the system achieves average and minimum illuminances of 11.56 lx and 5.30 lx, respectively. A complete single-luminaire failure reduces these values to 6.24 lx and 1.69 lx. Following fault detection, deterministic local self-healing increases the output of the adjacent luminaires and restores the corresponding values to 10.08 lx and 2.77 lx. The multiple-failure analysis demonstrates that spatially separated failures can remain locally recoverable, whereas adjacent simultaneous failures exceed the available luminous reserve and require maintenance intervention. Progressive-degradation simulations further show that compensation becomes necessary at 70% retained luminous-output health and maintains the adopted reference lighting requirements down to 40% health within the investigated range. The results demonstrate that real-photometry-based Digital Twins can distinguish normal, recoverable, and unrecoverable operating conditions and provide transparent, computationally lightweight temporary service restoration until physical maintenance is performed.

Keywords: Smart street lighting; digital twin; self-healing control; LED luminaire; fault resilience; adaptive dimming; EN 13201; photometric simulation; intelligent lighting.

INTRODUCTION

Street lighting is an essential urban infrastructure that supports nighttime visibility, road safety, and pedestrian mobility while representing a significant component of municipal electricity consumption. The widespread adoption of LED luminaires, sensing, communication networks, and intelligent controllers has transformed conventional street lighting into a distributed cyber-physical system capable of adaptive and energy-efficient operation [1]. Modern systems can dynamically adjust luminaire output according to traffic, pedestrian activity, environmental conditions, and predefined schedules, reducing energy consumption while maintaining required lighting conditions [2,3].

However, energy-efficient operation alone does not guarantee operational resilience. Luminaire degradation or complete failure can create locally under-illuminated road sections even when the

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remaining installation operates normally. Existing smart-lighting solutions increasingly incorporate automated fault detection and diagnostics [4], but identifying and reporting a failure does not restore the affected lighting service.

Digital Twin (DT) technology provides a suitable framework for extending monitoring toward operational decision support. A DT represents a dynamically updated virtual representation of a physical system that combines models and operational information [5–7]. Recent applications to lighting systems have demonstrated its potential for representing luminaire photometric behavior, degradation, and maintenance-related information [8,9]. Nevertheless, a gap remains between detecting an abnormal luminaire state and autonomously restoring the required road-surface lighting conditions.

This study addresses this gap through self-healing at the lighting-service level. Following luminaire degradation or failure, the DT evaluates the resulting photometric state and determines whether neighboring healthy luminaires have sufficient output reserve to compensate for the lost luminous contribution. Their output can then be temporarily increased until physical maintenance is performed. If adequate compensation is impossible, the system identifies that its self-healing capacity has been exceeded and maintenance is required.

To provide realistic photometric assessment, the proposed model uses the measured I(C,γ) luminous-intensity distribution of a commercial Philips RoadFlair Gen2 LED road luminaire rather than an idealized light-source model [11]. Lighting performance is evaluated using an EN 13201-oriented framework based on maintained average and minimum horizontal illuminance [12–14]. A deterministic local controller evaluates discrete compensation levels and selects the minimum adjustment capable of restoring the adopted reference conditions.

The framework is evaluated under healthy operation, complete single-luminaire failure, simultaneous multiple failures, and progressive luminous-output degradation. The main contributions are: (1) a DT-enabled architecture for local restoration of lighting performance; (2) integration of measured commercial-luminaire photometry; (3) EN 13201-oriented criteria for evaluating successful recovery; (4) a deterministic minimum-compensation strategy; and (5) explicit identification of recoverable and unrecoverable fault conditions.

DIGITAL-TWIN-ENABLED SELF-HEALING STREET-LIGHTING ARCHITECTURE

The proposed framework integrates a physical smart street-lighting installation with a synchronized Digital Twin (DT) and a deterministic self-healing controller. Its objective is to evaluate the photometric impact of luminaire degradation or failure and, when feasible, temporarily restore the required lighting conditions through local reconfiguration.

A. System Architecture

The architecture consists of four functional layers: the physical lighting system, monitoring and state acquisition, the DT, and supervisory self-healing control. The physical layer includes LED luminaires, dimmable drivers, and communication infrastructure. Each luminaire is represented by its position, mounting geometry, rated power, operating level, health state, and measured $I(C,\gamma)$ photometric distribution obtained from the manufacturer-provided IES file.

The monitoring layer supplies luminaire operating states to the DT. The present study assumes that degradation or failure has already been detected. The DT combines the updated operating state with the geometrical and photometric model to evaluate the resulting road-surface lighting conditions. If the requirements are violated, the supervisory controller evaluates local

compensation using neighboring healthy luminaires.

B. Digital Representation of Luminaire State

The state of luminaire i is represented by:

$$x_i(t) = [u_i(t), h_i(t), f_i(t)] \quad (1)$$

where $u_i(t)$ is the normalized output command, $h_i(t)$ is the luminous-output health factor, and $f_i(t)$ represents availability. Healthy operation $h_i = 1$, $f_i = 1$, whereas degradation is represented by $0<h_i<1$, and complete failure by $f_i = 0$.

The effective luminous contribution therefore depends on the commanded output, health, and availability.

C. Self-Healing Operating Principle

During normal operation, luminaires operate below their maximum output to preserve luminous reserve. Following detected degradation or failure, the DT recalculates the photometric state. If the lighting requirements are violated, the controller evaluates local compensation by neighboring healthy luminaires and selects the lowest-power feasible recovery state.

The deterministic formulation enables transparent evaluation of local recovery without machine-learning or reinforcement-learning methods.

D. Recovery and Self-Healing Capacity

The framework distinguishes three operating states:

- Normal: lighting requirements are satisfied without compensation.
- Self-healed: an abnormal condition exists, but local reconfiguration restores the required lighting performance.
- Maintenance required: no admissible local configuration can restore the reference conditions.

Thus, recovery depends on the fault location, installation geometry, photometric distribution, and available luminous reserve. The DT therefore acts as both a virtual representation of the installation and a supervisory mechanism for evaluating whether autonomous recovery is physically feasible.

PHOTOMETRIC AND MATHEMATICAL MODEL

The Digital Twin combines measured luminaire photometry, installation geometry, and operating state to evaluate healthy, degraded, faulted, and self-healed lighting conditions.

A. Real Luminaire and Photometric Data

The case study uses a Philips RoadFlair Gen2 BRP491 LED107/WW 80W 220–240V DM GM road luminaire with a nominal luminous flux of 10,700 lm and rated power of 80 W. Its manufacturer-provided IES file defines the measured directional luminous intensity $I = I(C, \gamma)$, where C and γ are the horizontal and vertical photometric angles. Intermediate values are obtained by interpolation without empirical correction of the original IES data.

B. Installation Geometry and Calculation Grid

A representative single-sided installation is considered with road width W=7m, mounting height H=10m, luminaire spacing S=21m, and lateral optical-center offset of 0.5m. The geometry remains fixed for all scenarios.

Following the adopted EN 13201-3-oriented calculation procedure, the road surface is represented by 10 longitudinal and 5 transverse calculation points, with $D=S/10$=2.1m, $d=W/5$=1.4m, resulting in a 10 × 5 grid (50 points) used for all operating states.

C. Illuminance Calculation

For luminaire i and calculation point p, the horizontal and three-dimensional distances are:

$$r_{ip} = \sqrt{\left[\left(x_p - x_i\right)^2 + \left(y_p - y_i\right)^2\right]} \quad (2)$$

$$R_{ip} = \sqrt{\left(r_{ip}^2 + H^2\right)} \quad (3)$$

and the vertical photometric an

$$\gamma_{ip} = \arctan\left(\frac{r_{ip}}{H}\right) \quad (4)$$

The luminous intensity toward the calculation point is obtained from the measured photometry as $I_{ip} = I(C_{ip}, \gamma_{ip})$. The corresponding horizontal illuminance contribution is:

$$E_{ip} = \mathrm{MF} \cdot u_i \cdot h_i \cdot f_i \cdot \frac{H}{R_{ip}} \quad (5)$$

where MF is the maintenance factor. The total illuminance at point p is:

$$E_p = \sum E_{ip} \quad (6)$$

The principal photometric indicators are:

$$E_{avg} = \frac{1}{N_{grid}} \sum E_p \quad (7)$$

$$E_{min} = \min\left(E_p\right) \quad (8)$$

$$U_0 = \frac{E_{min}}{E_{avg}} \quad (9)$$

where U_0 is used as a descriptive uniformity indicator.

D. Operating Conditions and Reference Requirements

A constant maintenance factor of MF=0.80 is used. Healthy luminaires normally operate at unormal=0.60, while the maximum self-healing command is u_{max}=1.00, providing a 0.40 output reserve.

The adopted P2 reference conditions are $E_{avg} \geq 10$lx, $E_{min} \geq 2$lx.

Both conditions must be satisfied for a lighting state to be considered acceptable. These thresholds are used for an EN 13201-oriented assessment and do not constitute formal compliance certification.

E. Degradation and Failure Representation

Gradual degradation is represented through the health factor with the luminous-intensity distribution scaled as:

$$I_{degradation}(C, \gamma) = h_i \cdot I_{healthy}(C, \gamma) \quad (10)$$

A complete luminaire failure is represented by $f_i = 0$, eliminating its illuminance contribution. The health factor represents a controlled photometric degradation state rather than a physical aging or remaining-useful-life model.

F. Electrical-Power Model

For the proof-of-concept, electrical power is assumed to scale linearly with the dimming command:

$$P_i = P_{rated} \cdot u_i \cdot f_i \quad (11)$$

where P_{rated} = 80 W.

The total installation power is:

$$P_{total} = \sum P_i \quad (12)$$

and the additional local power associated with self-healing is:

$$\Delta P_{local} = P_{healed} - P_{fault} \quad (13)$$

This quantity is used by the controller to identify the lowest-power feasible recovery configuration.

SELF-HEALING CONTROL STRATEGY

The self-healing controller operates above the photometric Digital Twin and aims to restore the lighting requirements defined in Section 3 using the minimum feasible local increase in commanded power.

A. Activation and State Update

The DT continuously evaluates the photometric state of the installation. Self-healing is activated only when a detected luminaire abnormality causes either reference requirement to be violated.

The abnormal state is assumed to have been identified by the monitoring layer. A detection delay of t_{det} = 20 s is considered in the dynamic single-failure scenario.

B. Local Compensation Search

Compensation is restricted to healthy luminaires neighboring the affected road section, while unaffected luminaires remain at their normal output. The admissible commands are U={0.60,0.70,0.80,0.90,1.00}.

For each candidate configuration u, the DT recalculates the road-surface illuminance distribution and verifies the photometric requirements defined in Section 3. Only healthy and available luminaires participate in the compensation process.

C. Minimum-Power Recovery

Among all feasible configurations, the controller selects the one requiring the smallest additional local commanded power relative to the uncompensated abnormal state:

$$\Delta P_{\text{local}}(u) = P_{\text{candidate}}(u) - P_{\text{failt}} \quad (14)$$

and:

$$u = \arg\min \Delta P_{\text{local}} \quad (15)$$

subject to the photometric requirements and $u_j \in U$.

Because the search is restricted to a small local neighborhood and five discrete output levels, the deterministic procedure remains computationally lightweight and transparent.

D. Recovery and Self-Healing Limit

After applying u, the DT verifies the resulting photometric state. If both reference requirements are restored, the installation enters a temporary self-healed state.

If no feasible configuration exists, the event is classified as MAINTENANCE REQUIRED. Partial photometric improvement is therefore not considered successful self-healing unless both requirements are restored.

For progressive degradation, compensation is activated only when degradation causes a violation of the reference conditions, avoiding unnecessary increases in neighboring-luminaire output.

E. Control Sequence

The supervisory procedure can be summarized as:

Monitor → Detect → Update DT → Evaluate Photometry → Search Local Compensation → Select Minimum-Power State → Verify Recovery.

If the requirements remain satisfied, no corrective action is required. If a feasible compensation state exists, temporary self-healing is applied; otherwise, physical maintenance is required.

CASE STUDY AND SIMULATION SCENARIOS

The proposed self-healing strategy was evaluated using a representative single-sided installation of 20 identical Philips RoadFlair Gen2 luminaires with measured IES photometry. The main simulation parameters are summarized in Table 1.

Table 1. *Main parameters of the investigated installation*

Parameter	Value
Number of luminaires	20
Luminaire	Philips RoadFlair Gen2 BRP491
Luminous flux / rated power	10,700 lm / 80 W
Arrangement	Single-sided
Road width / mounting height	7 m / 10 m
Luminaire spacing	21 m
Lateral offset	0.5 m
Maintenance factor	0.80
Normal / maximum output	60% / 100%
Dimming levels	60%, 70%, 80%, 90%, 100%
Calculation grid	10 × 5 (50 points)
P2 reference thresholds	Eavg ≥ 10 lx; Emin ≥ 2 lx
Fault-detection delay	20 s

Four operating scenarios were investigated.

A. Scenario S1 — Healthy Operation

All 20 luminaires operate normally with $h_i = 1, f_i = 1, u_i = 0.60$.

This scenario establishes the baseline photometric performance.

B. Scenario S2 — Single-Luminaire Failure

One luminaire undergoes complete failure $f_k : 1 \rightarrow 0$. Following the 20 s detection delay, the DT evaluates the affected lighting state and activates local compensation if required.

C. Scenario S3 — Multiple Failures

Three simultaneous two-luminaire failure configurations are investigated

- S3a: F={L_0,L_1} — adjacent failures;
- S3b: F={L_0,L_2} — failures with one-pole separation;
- S3c: F = {L_0, L_3} — failures with two-pole separation.

These cases evaluate the influence of failure location and separation on self-healing capability.

D. Scenario S4 — Progressive Degradation

One luminaire is progressively degraded from 100% to 40% retained luminous-output health h_k={1.00,0.95,0.90,…,0.40}.

At each degradation level, the uncompensated state is evaluated first, and self-healing is activated only if the reference lighting requirements are violated. No conclusions are drawn below 40% health.

E. Evaluation Metrics

Performance is evaluated using E_{avg}, E_{min}, the descriptive uniformity indicator U_0, and the additional local commanded power ΔP_{local}. Successful self-healing requires restoration of both reference lighting conditions defined in Section 3.

RESULTS AND DISCUSSION

A. Healthy Operation and Single-Failure Recovery

Under healthy operation at 60% output, the installation achieves E_{avg}=11.56lx, E_{min}=5.30lx, U_0 = 0.459, thus satisfying the adopted P_2 reference conditions. The corresponding illuminance distribution is shown in Figure 1.

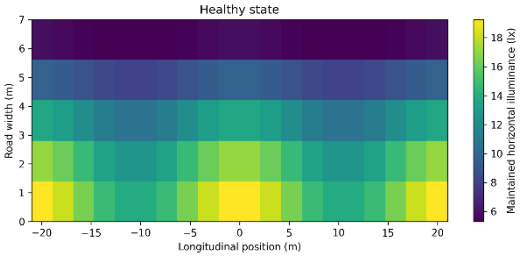


Fig. 1 *Healthy-state 2D illuminance distribution*

A complete single-luminaire failure reduces the performance to E_{avg}=6.24 lx, E_{min} = 1.69 lx, U_0=0.271, and both reference requirements are violated Figure 2.

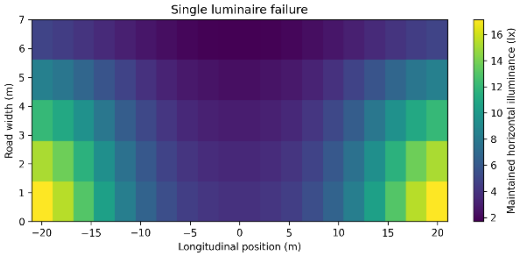


Fig. 2 *Single-luminaire failure*

Following the 20 s detection delay, the controller increases the two adjacent luminaires from 60% to 100%, 60% – 60% – OFF – 60% – 60% and → 60% – 100% – OFF – 100% – 60%.

The recovered state reaches E_{avg}=10.08lx, E_{min}=2.77lx, U_0 = 0.275, with ΔP_{local}=64W, restoring both reference conditions Figure 3.

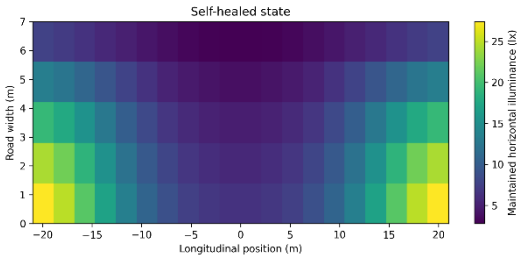


Fig. 3 *Self-healed illuminance distribution*

The controller therefore restores the required lighting service rather than reproducing the original healthy illuminance distribution. Figure 4 illustrates the dynamic response, including the modeled 20 s detection delay.

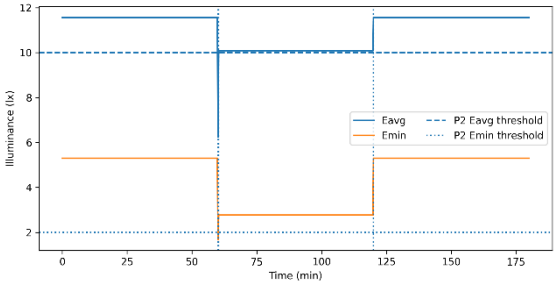


Fig. 4 *Dynamic single-failure response*

B. Multiple Failures

Table 2 summarizes the results for simultaneous two-luminaire failures.

The adjacent-failure case L0 + L1 remains below the required lighting levels even with maximum local support and is therefore classified as maintenance required. In contrast, the spatially separated L0 + L2 and L0 + L3 cases are recoverable with additional local commanded powers of 96 W and 64 W, respectively. This demonstrates that self-healing capability depends strongly on failure location and the remaining local luminous reserve. Figure 5 compares the three double-failure configurations and

highlights the strong influence of failure spacing on the achievable self-healing response.

Table 2. *Performance under simultaneous failures*

Failure configuration	State	E_{avg} (lx)	E_{min} (lx)	U_0	ΔP_{local} (W)	Recovery
L0 + L1	Fault	3.35	0.40	0.120	–	No
L0 + L1	Maximum support	5.59	0.67	0.120	128	No
L0 + L2	Fault	6.01	1.65	0.275	–	No
L0 + L2	Self-healed	10.01	2.75	0.275	96	Yes
L0 + L3	Fault	6.23	1.69	0.271	–	No
L0 + L3	Self-healed	10.08	2.77	0.275	64	Yes

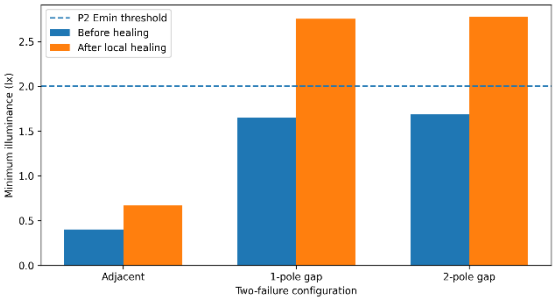


Fig. 5 *Comparison of multiple-failure configurations*

C. Progressive Degradation

Without compensation, the installation remains within the adopted reference conditions down to 75% retained luminous-output health. At 70% health, Eavg decreases to 9.96 lx, triggering self-healing.

Table 3 summarizes the recovered states from 70% to 40% health.

Within the investigated range, self-healing maintains both reference conditions down to 40% health, while the required additional local commanded power increases from 8 W to 32 W. The stepwise response results from the discrete dimming levels used by the controller. Figure 6 illustrates this progressive-degradation response and shows how increasing local compensation maintains the required lighting performance as luminaire health decreases.

Table 3. *Self-healing under progressive degradation*

Health	Eavg (lx)	Emin (lx)	ΔPlocal (W)
70%	10.44	4.47	8
65%	10.17	4.31	8
60%	10.39	4.38	16
55%	10.12	4.21	16
50%	10.30	4.32	24
45%	10.07	3.75	24
40%	10.29	3.64	32

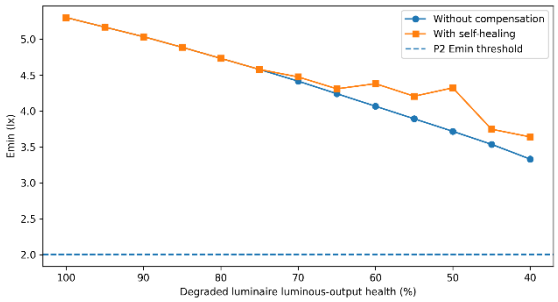


Fig. 6 *Progressive degradation and self-healing response*

D. Discussion

The results distinguish three operating regions: normal, recoverable, and unrecoverable. Recoverability depends on fault location, luminaire photometry, installation geometry, and available luminous reserve; therefore, identical numbers of failures may lead to different recovery outcomes.

Operating below maximum output provides reserve capacity for temporary self-healing. The Digital Twin evaluates whether this reserve is sufficient and applies local compensation when feasible; otherwise, the condition is classified as requiring maintenance.

LIMITATIONS AND FUTURE WORK

The present study is a simulation-based proof of concept. The photometric model uses manufacturer-provided IES data but has not yet been validated against field measurements or established lighting-design software; therefore, the adopted EN 13201-oriented criteria should not be interpreted as formal compliance certification. The model also assumes linear relationships between dimming, luminous output, and electrical power, while the 20 s fault-detection delay is prescribed rather than experimentally determined.

Progressive degradation is represented by a simplified luminous-output health factor rather than a physical aging or remaining-useful-life model. The case study is further limited to one luminaire type, installation geometry, and deterministic local control strategy. Future work will address experimental validation, measured degradation and asset-health modeling, and extension to larger lighting networks.

CONCLUSIONS

This study presented a Digital-Twin-enabled self-healing framework for resilient smart street lighting based on real luminaire photometry and deterministic local compensation. For the investigated installation, a complete luminaire failure reduced the average and minimum illuminances to 6.24 lx and 1.69 lx, while self-healing restored them to 10.08 lx and 2.77 lx, respectively.

The results confirm that the proposed Digital Twin can identify lighting-performance degradation, evaluate the available local compensation capacity, and distinguish between recoverable and maintenance-required conditions. The framework therefore provides a transparent and computationally lightweight approach for temporary restoration of lighting service following luminaire degradation or failure.

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