

Ecological and Smart Optimization of Green Infrastructure: Case of Bardo Urban Park (Constantine, Algeria)

Assia Kadri^{1*}, Salima Rayene Kadri¹, Khalil Khedairia¹, Ahlem Bouchema¹

¹ *University of Constantine 3 – Salah Boubnider*

"AVMF" Research Laboratory, Constantine, Algeria

* Corresponding author : assia.kadri@univ-constantine3.dz

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ABSTRACT

In a global context marked by intensifying environmental challenges, urban infrastructure management must integrate principles of sustainability and intelligence. Urban parks, as multifunctional public spaces, play a vital role in improving urban quality of life and delivering essential ecosystem services (thermal regulation, stormwater management, and biodiversity preservation). This paper focuses on the Bardo Urban Park (Constantine, Algeria) to develop an integrated approach to ecological and smart optimization. The methodology is built on a systemic framework combining environmental certification standards analysis (ISO 14001, HQE²R, LEED, BREEAM, and NBS), field surveys, architectural and technical diagnostics, risk analysis (Failure Mode, Effects, and Criticality Analysis – FMEA), and SWOT analysis. Results reveal contrasting performance: while plant diversity (5/6) and sustainable material use (5/6) are satisfactory, energy efficiency (1/6), water management, accessibility for people with reduced mobility, and waste management exhibit critical deficiencies (FMEA criticality ≥ 12). On this basis, a programmatic optimization guide is proposed around nine strategic axes, integrating smart technologies to transform the park into a sustainable and inclusive green infrastructure.

Keywords: Urban park, Green infrastructure, Sustainability, Environmental certification, Smart technologies, SWOT analysis, FMEA, Ecological optimization, Constantine.

Introduction And Context

In the face of accelerated urbanization and climate change, urban green spaces have emerged as strategic levers for the sustainable development of cities. Today, more than half of the world's population lives in urban areas, and this proportion continues to grow, exerting unprecedented pressure on urban ecosystems (Brzoska & Späße, 2020). According to Norton et al. (2023), urban parks constitute multifunctional green infrastructures capable of regulating ambient temperature, mitigating urban heat island effects, filtering air, managing stormwater, and supporting local biodiversity. The scientific literature confirms that green spaces positively contribute to the urban microclimate by creating a cooling effect through shading and evapotranspiration, while absorbing carbon dioxide and releasing oxygen (Guechi et al., 2021 ; Gherraz et al., 2020). Recent studies conducted in Constantine confirm the existence of a negative correlation between vegetation cover density (NDVI) and land

surface temperature (LST), thereby demonstrating that an increase in green spaces leads to a measurable reduction in urban temperatures (Louafi et al., 2024). Local research has also quantified the microclimatic gains associated with optimizing the green infrastructure ratio in the Constantine context (Sahnoune et al., 2021).

The environment, in its broadest sense, is defined as "everything that surrounds us, the totality of natural and artificial elements within which human life unfolds" (Thematic Approach, 2025). It combines natural components (air, water, soil, fauna, flora) and socio-economic elements that together constitute the framework and living conditions of a population. Augustin Berque further specifies that the environment is "the physical or factual dimension of the milieu, encompassing both artifacts and social relations." The environmental management of an urban park must rest upon several fundamental principles : prevention (averting environmental damage through appropriate measures prior to any development), information (maintaining knowledge of the state of the environment and of projects likely to affect it), participation (involving citizens in decision-making), the polluter-pays principle (internalizing external social costs), and precaution (adopting proportionate measures in the face of uncertain risks).

In Algeria, the circular of October 31, 1984, sets the minimum standards for green space development, prescribing in particular 4 m² per inhabitant for squares and public gardens, and up to 10 m² per inhabitant for spaces surrounding public buildings. Despite this regulatory framework, Algerian cities, including Constantine, suffer from a structural deficit in quality green spaces. This paradox between political discourse and territorial reality is embedded in a broader urban planning problem, where the provision of green spaces more often responds to event-driven and aesthetic considerations than to a genuine sustainable development strategy. The Bardo Urban Park, developed within the framework of the "Constantine, Capital of Arab Culture 2015" event, perfectly illustrates this ambivalence: built on a former 65-hectare urban wasteland resulting from the eradication of precarious housing, this project initially responded to a political will and a social demand for urban greening, yet its development prioritized image and landscape aesthetics over programming that would fully integrate ecological, functional, and social dimensions. The park site was historically an urban wasteland. Its conversion into a park responded to a political will to enhance this strategic sector, situated in immediate proximity to the city center and major heritage elements such as the Roman aqueduct, archaeological traces, and the medina of Constantine. Project management was carried out by the Environment Directorate of the Wilaya of Constantine, with a mixed Algerian-Italian consortium for design oversight and an Algerian-Spanish consortium for construction. The contract, amounting to 3,136,934,611.97 DZD, was executed over a 12-month period beginning November 26, 2014, with an overall completion rate of 65% (Environment Directorate of Constantine, technical data sheet). Field studies reveal that while the park enjoys high attendance and has become a popular destination for Constantine residents seeking relaxation, the emphasis placed on aesthetics to the detriment of local socio-economic needs raises fundamental questions of equity and sustainability. Recent research on the urban regeneration of the Bardo district confirms that although the park has significantly improved the urban image, its programming suffers from a lack of coherence with residents' expectations and with international standards for sustainable green infrastructure (Grina et al., 2024).

The programming of urban parks in Algeria thus suffers from the absence of operational frameworks that simultaneously integrate ecological, technological, and social requirements. Urban programming, which takes place upstream of a project, aims to establish the objectives, constraints, and requirements of an operation. It sits at the interface between the project owner and the project manager and concerns the mastery of building and equipment commissioning. According to Merlin and Choay (2005), programming is "the definition of the urban and architectural framework and the conditions for project implementation on behalf of the project owner." Planning, on the other hand, is a formalized procedure aimed at producing an outcome articulated as an integrated decision-making system. To plan is to "think about the future and control the future." The planning process comprises five stages : activity

definition (SWOT analysis), strategy formulation, operational plan development, budget determination, and results evaluation. The Bardo Urban Park represents an emblematic case study : a large-scale green infrastructure (65 ha) whose ecological and functional performance has never been the subject of a systematic evaluation. User surveys revealed a strong citizen attachment to this park, but also significant shortcomings in terms of maintenance, management, and accessibility. Accordingly, this research pursues four complementary objectives :

1. To assess the current ecological performance of the park using international environmental assessment frameworks, including the *International Organization for Standardization 14001* (ISO 14001), *High Environmental Quality for Urban Renewal* (HQE²R), *Leadership in Energy and Environmental Design* (LEED), *Building Research Establishment Environmental Assessment Method* (BREEAM), and *Nature-Based Solutions* (NBS) principles;
2. To identify and classify operational failures through field diagnostics and risk analysis;
3. To develop a programmatic optimization guide integrating smart technologies;
4. To contribute to a reproducible methodology for evaluating urban green infrastructure in semi-arid North African contexts.

The originality of this work lies in the unprecedented combination, within an Algerian context, of three complementary approaches: the cross-application of international environmental certification standards, the use of the *Failure Mode, Effects, and Criticality Analysis* (FMEA) method for risk classification of a green infrastructure, and the proposal of a "smart park"-oriented programmatic optimization guide. This approach responds to recent recommendations in the scientific literature emphasizing the necessity of developing evaluation methods adapted to the local specificities of urban ecosystems, particularly in semi-arid regions where water management and thermal regulation challenges are critical. As Brzoska and Späße (2020) emphasize, research on urban ecosystem services must descend to the scale of fine structures to produce operational results. It is precisely at this scale that our study of the Bardo Park is situated, whose analysis will contribute to building a national framework for the certification and optimization of green infrastructures in Algeria and North Africa

Literature Review

Urban parks as multifunctional green infrastructures

The recognition of urban parks as green infrastructures (GI) has gained prominence in the international literature over the past decade. Contrary to the traditional view that reduced them to recreational and aesthetic spaces, recent studies underscore their strategic role in urban resilience (Demuzere et al., 2014). These spaces deliver multiple ecosystem services: thermal regulation (reduction of urban heat islands), stormwater management, carbon sequestration, air quality improvement, and support for local biodiversity (Elmqvist et al., 2015 ; Norton et al., 2023). In semi-arid Mediterranean climates such as that of Constantine, this microclimatic regulation function is particularly crucial. A study by Marando et al. (2019) quantified that urban parks can reduce ambient temperatures by 2 to 5 °C during heat waves, with an influence radius extending up to 500 meters beyond their boundaries. Sahnoune et al. (2021) demonstrated that an optimized ratio of green roofs and green infrastructures can lower air temperature by 1.24 °C and surface temperature by up to 4 °C in the Constantine context. This performance depends on vegetation density and structure (Ziter et al., 2019), as well as on the presence of water bodies (Gunawardena et al., 2017). Studies conducted in Guelma (Algeria) revealed a negative correlation between vegetation cover density and land surface temperature, confirming that increasing green spaces reduces urban temperatures (Guechi et al., 2021; Guechi et al., 2022).

Environmental certification of urban green spaces

The application of environmental certification systems to green infrastructures is an emerging field. Initially designed for buildings (LEED, BREEAM) or neighborhoods (HQE²R), these frameworks are

progressively being adapted to urban parks (Brown et al., 2020 ; Wang et al., 2024). Several critical studies highlight their limitations : they often prioritize measurable technical criteria (water consumption, percentage of recycled materials) over more qualitative dimensions such as user experience or landscape integration (Berardi, 2013 ; Castleton et al., 2020).

The "Sustainable Sites Initiative" (SITES) framework, developed in the United States, represents a significant advancement, as it is specifically dedicated to landscape developments (SITES, 2014). It incorporates criteria for soil management, vegetation selection adapted to the biogeographic context, and hydrological performance.

However, these tools remain rarely applied to parks outside Western countries, and no previous study has cross-referenced five frameworks (ISO 14001, HQE²R, LEED, BREEAM, NBS) on an Algerian park. Our research aims to help fill this gap.

Smart technologies for urban park management

The integration of smart technologies into urban green space management is experiencing rapid growth, building upon the smart city concept (Albino et al., 2015 ; Bibri & Krogstie, 2017). Several categories of technologies are employed :

IoT sensors for water management : Recent studies (Salis et al., 2025 ; Romanov & Galelyuka, 2025) demonstrate that soil moisture sensor networks coupled with machine learning-based predictive models can reduce irrigation water consumption by 30 to 50% in urban parks, while maintaining satisfactory vegetation health. Pilot deployments in Barcelona (Marchi et al., 2021) and Singapore (Wong et al., 2020) confirm these gains.

Smart lighting : Replacing conventional lighting with connected solar LEDs equipped with presence detection enables energy savings on the order of 60 to 80%, according to Carli et al. (2020). These systems also enhance perceived user safety.

Waste management : Connected waste bins fitted with fill-level sensors and GPS-optimized collection routes have become standard practice in major metropolises (Anagnostopoulos et al., 2017). Their deployment in medium-sized parks (10–50 ha) has demonstrated collection cost reductions of 25 to 40% (Kubba & Hattab, 2022).

Citizen participation and governance : Mobile applications dedicated to urban parks , encompassing incident reporting, space reservation, and educational programs , are identified in the literature as a lever for improving governance and fostering citizen ownership (Afzalan et al., 2017; Falco & Kleinhans, 2018).

Risk assessment in green infrastructures

Risk analysis applied to green infrastructures remains an underexplored field. The *FMEA* method (Failure Mode, Effects, and Criticality Analysis), widely used in industry, has been adapted on a limited number of occasions to urban green spaces (Khedairia et al., 2022). Its advantages lie in its systematic nature and its capacity to prioritize corrective actions (Stamatis, 2003). Nevertheless, its application to an urban park remains exceedingly rare, and our study constitutes the first systematic application of *FMEA* to an Algerian park, thereby enabling an objective prioritization of interventions.

The Algerian and North African context

The Algerian context has been the subject of several structural assessments. Bouzidi (2019) and Madani and Belguidoum (2018) highlighted the quantitative and qualitative deficit of green spaces in Algerian cities. More recently, Grina et al. (2024) analyzed the impact of the Bardo Park on the neighborhood's image, but without conducting a systemic evaluation of its ecological and functional performance. Yet, as Brzoska and Spāže (2020) emphasize, research on urban ecosystem services must necessarily descend to the scale of fine structures (individual parks, gardens, tree alignments) in order to produce

operational results that can be integrated into planning documents. It is precisely at this scale that our study of the Bardo Park is situated.

The literature on urban parks in North Africa is relatively scarce compared to European or North American contexts. Several studies have nevertheless documented the structural deficit of green spaces in Algerian cities (Bouzidi, 2019; Madani & Belguidoum, 2018). This deficit is exacerbated by land pressure, weak maintenance budgets, and the lack of specialized training for managers (Bouamama et al., 2018).

The Bardo Park has been the subject of a few recent publications. Grina et al. (2024) analyzed its impact on the transformation of the Bardo neighborhood's image, concluding that while the aesthetic improvement was undeniable, the socio-economic benefits for local residents were limited. Esma and Ahcène (2025) compared the Bardo Park to the El Mridj recreational forest, highlighting the former's superior tourist attractiveness but the latter's greater naturalness. No previous study has proposed a systemic evaluation of the park's ecological and technical performance, nor an optimization guide integrating smart technologies. The present research aims to fill this gap.

Research positioning

As the foregoing developments demonstrate, our research is positioned at the intersection of the five fields covered by this literature review : green infrastructures, environmental certification, smart technologies, risk analysis, and the Algerian context. Each of these fields has seen significant advances, yet their combination and application to an Algerian urban park in a semi-arid climate constitute a scientific blind spot. Demuzere et al. (2014), Norton et al. (2023), and Elmqvist et al. (2015) have firmly established the multifunctional character of green infrastructures, but their work has been predominantly conducted in temperate or humid tropical contexts, leaving a gap concerning semi-arid Mediterranean climates such as that of Constantine. Similarly, environmental certification frameworks (Brown et al., 2020 ; Wang et al., 2024 ; SITES, 2014) offer objective performance criteria, yet their application to parks outside Western countries remains exceptional. Smart technologies applied to green spaces (Salis et al., 2025 ; Romanov & Galelyuka, 2025 ; Marchi et al., 2021) demonstrate measurable gains, but no study has, to date, adapted these solutions to the Algerian context. Finally, while the *FMEA* method has proven its utility for prioritizing corrective actions (Khedairia et al., 2022 ; Stamatis, 2003), its application to an urban park remains exceedingly rare. Our research therefore fills these gaps by proposing an original methodology combining cross-referenced diagnosis, *FMEA*, and SWOT analysis, culminating in a reproducible operational guide for urban parks in semi-arid North African climates.

Methodology

Study site presentation

The Bardo Urban Park is located at the locality of "Bardo," the capital of the commune of Constantine (northeastern Algeria) (Figure 1). Covering an area of approximately 65 hectares, it constitutes one of the largest urban parks in Algeria. Its topography is rugged : the first zone covers nearly the entire terrain, consisting of continental Mio-Pliocene clays and silts, with slopes ranging from 15 to 25%; the second zone features Priabonian clays with blocks, with similar slopes. The climate is semi-arid Mediterranean, characterized by dry and hot summers (maximum temperatures: 32–48 °C in August) and cold and humid winters (minimum temperatures: 2–6 °C in January). The Bardo Urban Park is part of a broader urban regeneration project for the Constantine metropolis. It aligns with the orientations of the CMMP (Constantine Metropolis Modernization Plan), which aims to foster regional dynamism and influence through the enhancement of territorial potential, particularly through the environmental and aesthetic quality of public spaces that structure the urban environment (Figure 1). The analysis of the regulatory and programmatic context also drew upon the urban planning

instruments in force in Algeria: the MPDU (Master Plan for Development and Urban Planning) to assess long-term development impacts, the LUP (Land Use Plan) to evaluate architectural and urban quality, and the CDP (Communal Development Plan) to understand the commune's green space development strategy.

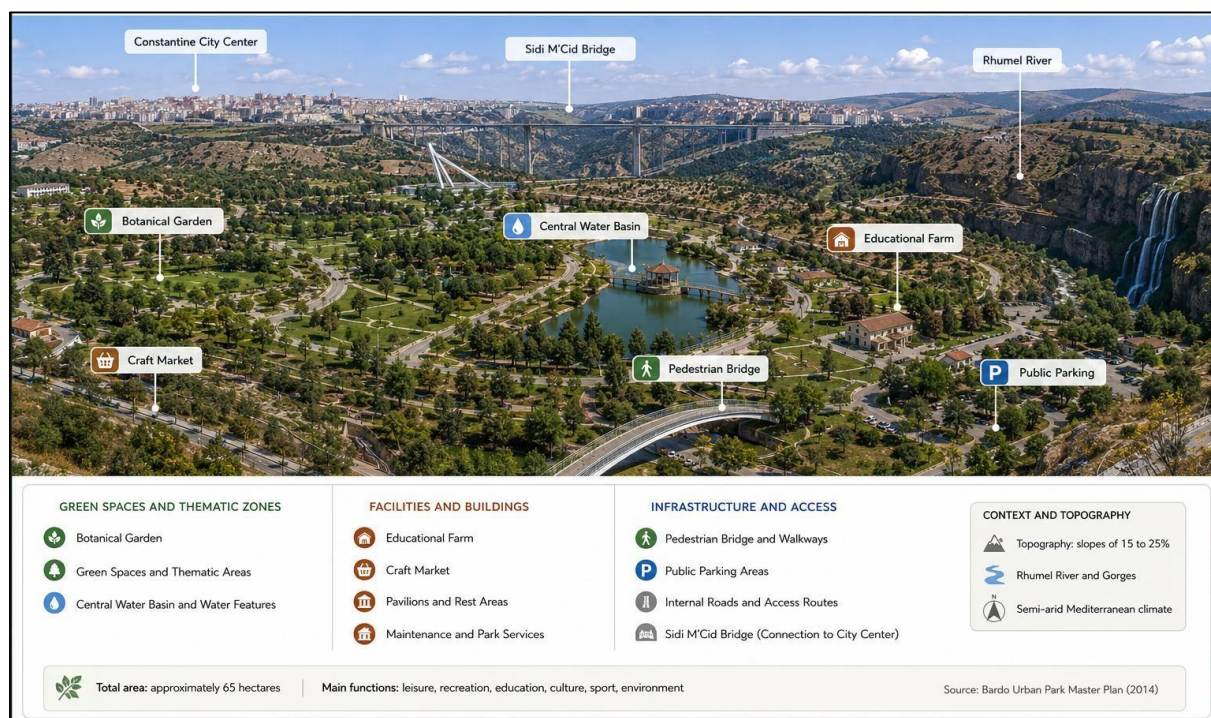


Figure 1. Panoramic view of the Bardo Urban Park

Methodological framework

The adopted methodology is structured in two complementary and sequential phases : a theoretical phase devoted to constructing the evaluation framework, and an empirical phase of field investigation (Figure 2) :

Phase 1 : Theoretical analysis and framework construction

A requirements framework was constructed through the cross-referencing and synthesis of five benchmark environmental certifications : ISO 14001, HQE²R, LEED, BREEAM, and NBS. The HQE²R approach was used as the structuring framework (Table 1). This method, developed at the neighborhood scale, rests on a targeting logic : it breaks down environmental objectives into targets, sub-targets, and quantifiable indicators. In our study, the application of the HQE²R approach enabled the park to be evaluated according to 14 targets distributed across four families : eco-construction (harmonious building-environment relationships, integrated selection of products and processes, low-impact construction sites), eco-management (energy, water, operational waste, and maintenance management), comfort (hygrothermal, acoustic, visual, olfactory), and health (sanitary quality of spaces, air, and water).

Table 1. Environmental certification frameworks employed

Certification	Origin	Main domain	Criteria retained
ISO 14001	International	Environmental management system	Water, energy, waste, biodiversity
HQE ² R	France/Europe	Sustainable neighborhood development	Quality of life, governance, environment
LEED	United States	Energy and environmental performance	Sustainable sites, energy, materials
BREEAM	United Kingdom	Environmental assessment of buildings	Health, energy, transport, water
NBS	International	Nature-Based Solutions	Biodiversity, ecological resilience

Source : Authors.

Phase 2 : Empirical investigation

The field investigation employed three complementary tools.

(a) *Field surveys* : Repeated visits were conducted to observe and evaluate eight parameters : waste management, function and activity management, transport management, safety, energy efficiency, sustainable materials, water efficiency, and plant diversity. An architectural and technical diagnostic grid was used, enabling scoring on a 20-point scale per parameter, supported by documentary photographs.

(b) *Diagnostic grid* : A grid structured in five columns (Parameter , Sub-parameter , Indicator , Sub-indicator , Evaluation) was used to collect quantitative and qualitative data on spaces, materials, equipment, and infrastructure. It comprises 8 main parameters broken down into 32 sub-parameters.

To complement the environmental assessment, we employed the ENVI model (*Environnement Impact*), which structures the analysis around five environmental variables : soil stability, topographic adaptation, stormwater management, biodiversity preservation, and air quality. This model was applied to the Bardo Park and, for comparative purposes, to the Jean-Drapeau Park in Montreal (Île Sainte-Hélène), in order to benchmark the Constantine site's performance against an international reference in urban green infrastructure.

(c) *Risk analysis : FMEA method* : The *FMEA* method (Failure Mode, Effects, and Criticality Analysis) was applied to identify, classify, and prioritize the park's failures. Each failure was rated according to two criteria : Occurrence (O), which evaluates the frequency of failure occurrence, and Severity (G), which measures the severity of its consequences. The Criticality index (C) is calculated as the product of these two criteria : $C = O \times G$. The critical threshold is set at $C \geq 8$, beyond which priority corrective action is required.

SWOT Analysis

The data from field surveys and the diagnostic grid were synthesized in a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats). This cross-analysis made it possible to identify priority optimization axes and to formulate operational recommendations for an ecological and smart park programming guide.

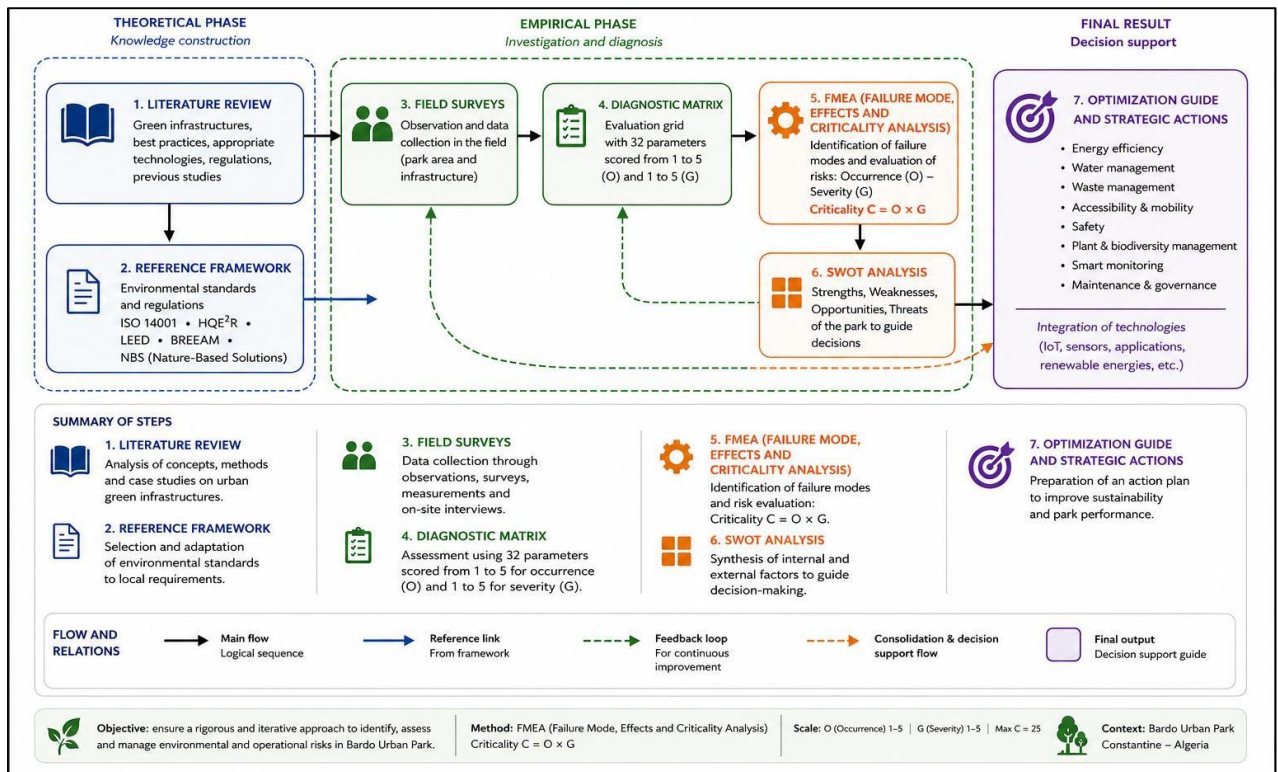


Figure 2. Synthetic methodological approach for the ecological and smart optimization of a green infrastructure. Case of the Bardo Urban Park (Constantine, Algeria.)

Source : Authors

Results

Diagnostic grid results

The systematic evaluation presented in Table 2, based on the diagnostic grid applied to the eight main parameters, produced the following scores (expressed out of 6 in the synthetic assessment and converted to scores out of 20 in the detailed evaluation):

Table 2: Evaluation scores by parameter (Diagnostic grid)

N°	Parameter	Score /6	Score /20	Level
01	Plant diversity	5/6	17/20	✓ Satisfactory
02	Sustainable materials	5/6	16/20	✓ Satisfactory
03	Function management	3/6	11/20	△ Average
04	Waste management	2/6	7/20	✗ Insufficient (FMEA : C = 12)
05	Water management	1/6	4/20	✗ Critical
06	Transport & PRM accessibility	1/6	4/20	✗ Critical
07	Energy efficiency	1/6	3/20	✗ Very critical
08	Safety	1/6	5/20	✗ Insufficient (FMEA : C = 8)

The architectural diagnosis of the "building and equipment" lot of the Bardo Park, conducted according to HQE targets, reveals several complementary shortcomings. Regarding visual comfort, the Bardo House (which houses the reception area, commercial spaces, and an exhibition space) uses curtain walls in clear transparent and semi-translucent glazing. While this design provides optimal natural lighting in terms of comfort and energy savings, the absence of solar protection devices generates risks of overheating and glare. Artificial lighting remains inadequate (75 W halogen lamps, 26 W EUREKA compact lamps, 75 W incandescent lamps) relative to the standards of a smart urban park. Acoustic comfort is not ensured, as no sound insulation measures were planned between the different premises. Finally, the open-air theater, a central element of the park, exhibits characteristics below standard : its current width is 4.20 m compared to 5.70 m under standardized conditions, and the number of projectors has decreased from 40 to 12.

SWOT Analysis

The diagnostic results were synthesized in a SWOT analysis (Table 3 & Figure 3), which cross-references the park's strengths and opportunities against its weaknesses and threats across seven dimensions

Table 3. Synthetic SWOT analysis of the Bardo Urban Park

Dimension	⊕ Strengths & Opportunities	⊖ Weaknesses & Threats
Vegetation	Score 5/6. Floristic richness : deciduous, evergreen, and fruit trees. Natural setting favorable to biodiversity.	Inadequate maintenance = allergy risks. Absence of thematic gardens. Steep slopes (15–25%) limiting certain developments.
Materials	Score 5/6. Certified wood, recycled concrete, stainless steel, natural stone.	Lack of overall material coherence. Absence of systematic monitoring of the carbon footprint of materials used.
Energy	Partial presence of LED lighting. High sunshine levels (favorable for PV panels).	Score 1/6. No renewable energy. Total dependence on the conventional power grid.
Water	Topography favorable to gravitational rainwater collection. Potential for phytoremediation.	Score 1/6. Criticality = 12. No rainwater harvesting system. Inefficient irrigation.
Waste	Available space for sorting infrastructure. Composting potential.	Score 2/6. Criticality = 12. Absence of selective sorting, recycling, or composting.
Accessibility & Transport	Sufficient area to integrate soft mobility lanes.	Score 1/6. Criticality = 12. No public transport nearby. Paths not accessible to PRM.
Safety	Sufficient area for secured zoning.	Score 1/6. Criticality = 8. Lack of fencing, slippery surfaces. Absence of fire extinguishers.

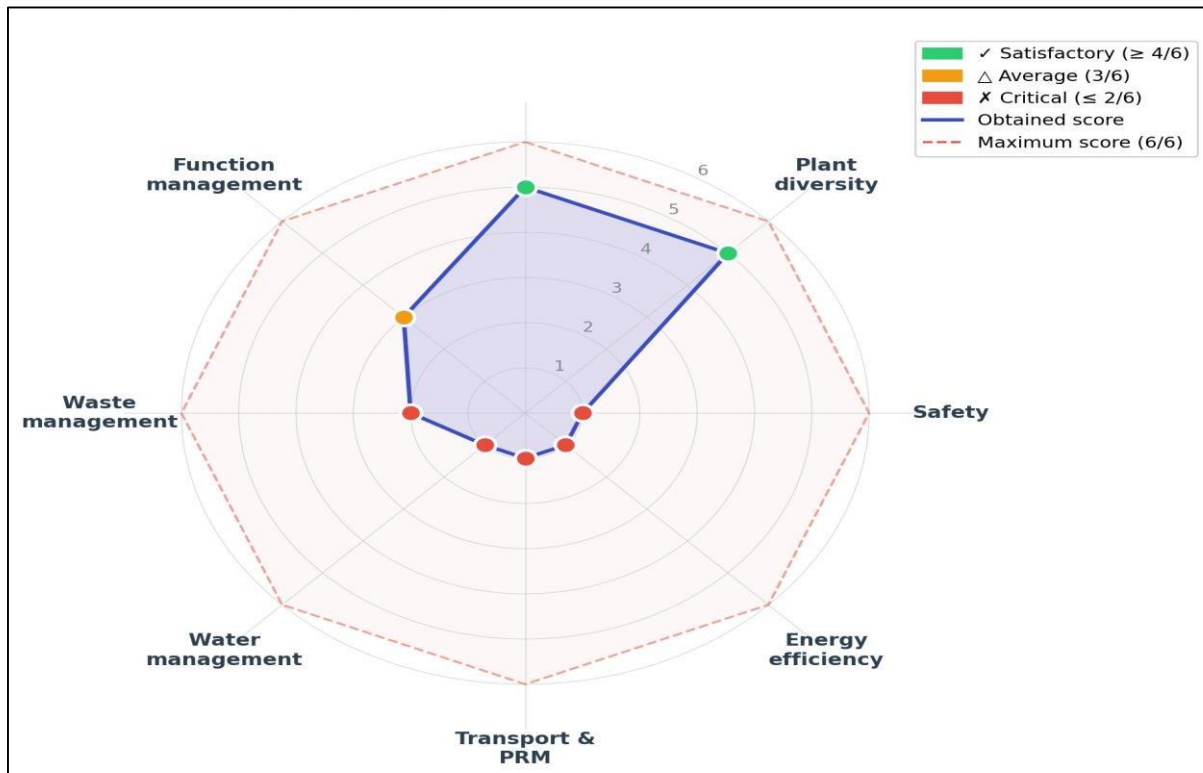


Figure 3. Environmental and sustainable performance score diagram of the Bardo Urban Park
Source : Authors

FMEA Analysis : Risk Classification

The application of the FMEA method to the six identified risks produced the criticality scores presented below (Table 4).

Table 4 : FMEA Results : Risk Criticality (★ = critical priority ≥ 12)

Risk	Type	Occurrence (O)	Severity (G)	Criticality (C = O × G)	Priority action
Drought / Water waste	Environmental	4	3	12 ★	Drip irrigation + weather sensors
Pollution / Absence of waste management	Environmental	4	3	12 ★	Smart selective sorting + composting
Pollution / Absence of renewable energy	Environmental	4	3	12 ★	PV panels + solar lighting
PRM inaccessibility	Human	4	3	12 ★	Ramps + adapted paths + signage
Visitor insecurity	Human Safety	2	4	8	Fencing + video

		2	4	8	surveillance + lighting
Landslide	Natural	2	4	8	Geotechnical study + stabilizing revegetation

Legend : (O) : Red = High, Green = Low ; (G) : Red = Severe, Orange = Medium ; (C) : Red = Critical, Orange = Medium.

Source : Authors.

The failure analysis was also broken down by operational phase. In the upstream phase, the following were identified : poor quality of pedestrian access and absence of a wearing course for mechanical access, lack of bus shelters (absence of public transport in the vicinity), failure to apply the precautionary principle and environmental concerns, and absence of a sustainable mobility plan. For these failures, the proposed action plans include : creating wearing courses with asphalt concrete to improve comfort, and systematic application of the environmental protection principle. In the operational phase, the following were noted : absence of eco-construction, failure to apply ISO 14001 standards in coating materials, absence of eco-management (insufficient maintenance), and lack of visual comfort and acoustic insulation measures. The proposed corrective actions include : use of cost-effective materials (zigzag concrete), enhancing circulation areas and gathering spaces through inert and plant materials, and optimizing the traceability of maintenance operations.

Discussion

The results obtained highlight a fundamental paradox of the Bardo Urban Park: designed as a showcase of Algerian urban modernity, the park possesses undeniable natural assets yet suffers from insufficient functional and technical programming relative to international sustainability standards. The energy score of 1/6 illustrates an exclusive dependence on the conventional power grid. Yet IoT technologies for monitoring urban green spaces are now mature and deployed in numerous European cities, enabling real-time management of tree health, soil moisture, and air quality (Romanov & Galelyuka, 2025). Salis et al. (2025) demonstrate that a system integrating sensors and machine learning-based predictive models can optimize irrigation in public parks. Similarly, the maximum criticality score (12) obtained for water management underscores the urgency of intervention. Nature-based solutions (phytoremediation, retention basins) combined with connected moisture sensors represent an appropriate response to Constantine's semi-arid context.

The programming and management difficulties of the Bardo Urban Park are embedded in a broader institutional and budgetary context. Algeria's environmental sector is structured around the Ministry of Territorial Planning and the Environment (MATE), established in 2000, and its local directorates. Analysis of finance laws between 2010 and 2020 reveals that the budget allocated to the environmental sector remained structurally low, fluctuating between 0.04% and 0.36% of the total state financing budget. The 2016 peak (0.36%) corresponds to the period of the Bardo Park's construction within the framework of "Constantine, Capital of Arab Culture 2015," confirming the exceptional and event-driven nature of this funding rather than a structural policy favoring green infrastructures. Furthermore, the circular of October 31, 1984, setting minimum green space standards (4 m²/inhabitant for squares and public gardens) has never been updated or made legally enforceable, and the planning instruments, namely the RCPH (General Census of Population and Housing), the MPDU, and the LUP, do not incorporate specific data or binding objectives regarding urban parks. This weakness in the normative and budgetary framework partly explains the deficits observed in energy efficiency, water management, and accessibility.

Programmatic optimization guide for the Bardo Park : 9 strategic axes

The proposed programmatic guide is structured around nine complementary strategic axes. It constitutes the operational translation of the diagnostic results, the SWOT analysis, the FMEA classification, and the certification frameworks. Its nine strategic axes are not independent: they form an integrated system in which each intervention produces cross-cutting effects across several dimensions of park performance. The prioritization of axes is based on the FMEA criticality level and the diagnostic grid scores, following a logic of decreasing urgency. The nine axes, their proposed measures, and associated smart technologies are detailed below (Table 5).

Table 5. Programmatic optimization guide for the Bardo Park : 9 strategic axes

Strategic axis	Type	Proposed measures	Smart technologies
ENVIRONMENT & RESOURCES			
Energy efficiency	Environmental	PV panels on shade structures and kiosks. 100% solar LED public lighting.	Smart meters, light sensors, centralized energy management
Efficient water management	Environmental	Rainwater harvesting. Drip irrigation. Retention basins. Phytoremediation.	Soil moisture sensors, weather sensors, automatic irrigation system
Waste management	Environmental	Selective sorting with differentiated bins (3–5 streams). Composting of organic waste.	Fill-level sensors, GPS-optimized collection, mobile application
SOCIAL & SAFETY			
Accessibility and soft mobility	Human	PRM access ramps. Adapted signage (braille). Electric bicycle stations.	Charging stations, accessible navigation application
Safety	Human Safety /	Fencing around the entire perimeter. Fire extinguishers and hydrants. Non-slip surfaces.	Smart video surveillance, connected fire alert system
ECOLOGY & DEVELOPMENT			
Plant diversity and biodiversity	Natural	Thematic gardens. Indigenous plants. Ecological corridors.	Air quality sensors, phenological monitoring by IoT
Functions and activities	Human	Multi-age playgrounds. Relaxation areas. Cultural spaces.	Space reservation application, interactive screens, public Wi-Fi
Sustainable materials	Environmental	Generalization of sustainable materials (recycled concrete, FSC wood, recycled steel).	Carbon footprint monitoring through environmental BIM
GOVERNANCE & DIGITAL			
Communication and governance	Human	Interactive information panels. Educational activity programs.	Park mobile application, real-time management dashboard, citizen participation platform

Category 1 : Environment and resources (Axes 1, 2, 3) : critical priority

The first three axes (energy efficiency, water management, and waste management) directly address the most severe deficiencies identified by the diagnostic (scores of 1/6, 1/6, and 2/6 respectively) and the maximum *FMEA* criticalities ($C = 12$ for each). These axes constitute the foundation of any intervention, as they determine the park's ecological and economic viability in the medium term.

Axis 1 (energy efficiency) aims to break the total dependence on the conventional power grid, observed during the diagnostic (score 1/6, i.e., 3/20). Installing photovoltaic panels on existing shade structures and kiosks would exploit Constantine's high sunshine levels (an asset identified in the SWOT), while the complete replacement of lighting with solar LEDs would, according to Carli et al. (2020), achieve savings of 60 to 80%. Smart meters and light sensors would ensure centralized real-time management, in line with the recommendations of Romanov and Galelyuka (2025) for green space supervision in the smart city context.

Axis 2 (water management) addresses the most urgent criticality ($C = 12$, score 1/6). In a semi-arid climate, the total absence of rainwater harvesting and inefficient irrigation constitute a systemic risk for vegetation sustainability. The guide proposes an integrated approach combining nature-based solutions (retention basins, phytoremediation) and IoT technologies (soil moisture sensors, weather sensors, automatic irrigation). This combination is validated by the work of Salis et al. (2025) and Marchi et al. (2021), who demonstrate water consumption reductions of 30 to 50% in parks equipped with similar systems. The site's rugged topography (slopes of 15 to 25%), identified as a constraint in the SWOT, paradoxically constitutes an asset for gravitational rainwater collection.

Axis 3 (waste management) addresses a major deficiency ($C = 12$, score 2/6) : the total absence of selective sorting, recycling, and composting. The deployment of differentiated bins (3 to 5 streams) equipped with fill-level sensors, coupled with GPS-optimized collection, aligns with practices now proven in major metropolises (Anagnostopoulos et al., 2017), yielding collection cost reductions of 25 to 40% (Kubba & Hattab, 2022). Composting organic waste would additionally produce soil amendments for the park, thereby promoting circular and integrated resource management and creating a virtuous cycle between waste management and vegetation maintenance.

Category 2 : Social and safety (Axes 4, 5 : high priority)

Axes 4 and 5 address the human and safety dimensions of the park. PRM accessibility (Axis 4) exhibits an *FMEA* criticality of 12 and a diagnostic score of 1/6, reflecting the absence of ramps, adapted paths, and inclusive signage. The proposed measures : access ramps, braille signage, electric bicycle stations, aim to ensure universal accessibility, complemented by charging stations and an accessible navigation application. These interventions respond to both regulatory requirements and the inclusivity criteria of the HQE²R and LEED frameworks.

Axis 5 (safety) presents a different risk profile : while the diagnostic score is low (1/6, i.e., 5/20), the *FMEA* criticality is 8 (moderate occurrence $O = 2$, but high severity $G = 4$), placing it in the monitoring zone rather than the critical zone. This difference between the diagnostic score and the *FMEA* criticality is explained by the fact that the diagnostic grid evaluates the state of safety equipment (very insufficient), whereas the *FMEA* evaluates the probability and severity of actual incidents (relatively rare but potentially serious). Perimeter fencing, non-slip surfaces, and fire extinguishers constitute the basic corrective measures, reinforced by smart video surveillance and a connected fire alert system.

Category 3 : Ecology and development (Axes 6, 7, 8) : consolidation and enhancement

Axes 6, 7, and 8 build on the park's existing strengths to further enhance quality. Axis 6 (plant diversity and biodiversity) leverages the high vegetation score (5/6) to go further : thematic gardens, ecological corridors, and indigenous plants adapted to the semi-arid climate. Integrating air quality sensors and IoT-based phenological monitoring would enable the quantification of ecosystem services provided by vegetation, thereby responding to the recommendations of Brzoska and Späße (2020) regarding the need to produce operational data at the scale of fine structures.

Axis 7 (functions and activities) addresses the average function management score (3/6) and the absence of thematic gardens identified in the SWOT. Creating multi-age playgrounds, relaxation areas, and cultural spaces, coupled with a space reservation application and interactive screens, aims to diversify the programmatic offer and strengthen citizen ownership of the park, in line with the recommendations of Afzalan et al. (2017).

Axis 8 (sustainable materials) builds on the satisfactory score obtained (5/6). The SWOT analysis revealed that while the park already uses certified wood, recycled concrete, and stainless steel, systematic monitoring of material carbon footprints is lacking. The introduction of environmental BIM for monitoring this footprint would enable a shift from ad hoc material selection to integrated life-cycle material management, in accordance with BREEAM and LEED criteria for environmental traceability.

Category 4 : Governance and digital (Axis 9) : cross-cutting lever

Axis 9 (communication and governance) plays a cross-cutting catalytic role for the entire guide. Interactive information panels and educational activity programs aim to strengthen users' environmental awareness. The park's mobile application serves as the unified interface enabling incident reporting, space reservation, and citizen participation, as recommended by Falco and Kleinhans (2018). The real-time management dashboard, fed by all IoT sensors deployed across Axes 1 through 6, provides managers with a consolidated view of park performance and operational alerts. Finally, the citizen participation platform responds to the fundamental principle of environmental governance identified in the introduction : involving citizens in decisions concerning their living environment.

Inter-axis synergies and systemic coherence

The guide's strength lies in its inter-axis synergies. Axis 1 (PV panels) supplies energy to the IoT technologies deployed in Axes 2 (moisture sensors), 3 (fill-level sensors), 5 (video surveillance), and 9 (dashboard), creating energy autonomy for the entire smart device system. Axis 2 (water management) supports Axis 6 (biodiversity) by ensuring optimized irrigation of ecological corridors. Axis 3 (composting) produces organic amendment that benefits Axis 6 (plant diversity). Axis 4 (accessibility) conditions the effectiveness of Axis 7 (functions) by ensuring universal access to programmed spaces. Finally, Axis 9 (digital governance) serves as the central coordination and supervision platform integrating and steering all interventions. This systemic architecture ensures that the guide does not reduce to a list of isolated measures but constitutes a coherent program for transforming the Bardo Urban Park into a smart, sustainable, and inclusive green infrastructure.

Conclusion And Perspectives

This study has demonstrated that the Bardo Urban Park, despite its undeniable natural assets : a 65-hectare area, high plant diversity (5/6), and satisfactory use of sustainable materials (5/6), exhibits major structural deficiencies in critical areas : energy efficiency (1/6), water management (1/6), PRM accessibility (1/6), and waste management (2/6). The application of the *FMEA* method objectified these failures, with criticality indices reaching 12/16 for priority environmental risks.

The programmatic optimization guide proposed across nine strategic axes constitutes an operational response to these deficiencies, combining conventional architectural and landscape interventions with the integration of smart technologies. This approach aligns with recent developments in "smart cities," where sensor networks enable the cost-effective deployment of multi-use solutions for green space management.

Future research should focus on: (1) instrumenting the park to collect real-time performance data via IoT sensor networks; (2) evaluating the impact of the proposed optimizations through numerical modeling; (3) extending the SWOT-*FMEA* methodology to other Algerian urban parks in order to build

a national framework for green infrastructure certification; (4) integrating a participatory dimension into park governance, as recommended in European urban resilience projects.

Study limitations

This research has several limitations that must be acknowledged in order to guide future work. The diagnostic grid scoring, while systematic, retains a degree of subjectivity inherent to field observation. The absence of instrumental quantitative data (actual energy consumption measurements, water volumes used, attendance data) limits the scope of conclusions. The findings are drawn from a single case study, situated in a specific climatic and socio-cultural context (semi-arid, northeastern Algeria). Direct transferability to other parks requires adaptations. Finally, the study reflects a state at a given point in time. Seasonal variations, attendance fluctuations, and the impact of maintenance interventions could not be incorporated.

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