

RESEARCH NOTE

Closing the Loop in Fan-Zone Sustainability: Integrating WSN/IoT Sensing, Footprint Attribution, and Digital Twins for Real-Time Decision Support

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Abstract

Purpose: Fan zones have become central to mega-events, yet sustainability assessment and decarbonization guidance remain largely venue-centric. This article develops a standardized, operationally actionable framework to measure, attribute, and mitigate fan-zone ecological impacts in real time under safety and experience constraints.

Design/methodology/approach: Building on sport-event footprint research, ecological-footprint approaches, and smart-city advances in WSN/IoT telemetry and Digital Twins, we develop a conceptual reference architecture that integrates a sensing layer, an attribution layer, and a Digital Twin layer for scenario testing and multi-objective optimization.

Findings: The framework specifies fan-zone system boundaries across mobility, operations, and materials; defines auditable KPI outputs; and links real-time data streams to mitigation levers through coupled models of pedestrian dynamics, energy loads, and waste logistics, embedded in multi-stakeholder governance.

Originality/value: The paper addresses methodological fragmentation by translating measurement into operational decision support, providing a fan-zone-specific sustainability architecture designed for benchmarking, adaptive control, and responsible deployment.

KEYWORDS

Fan zones; mega-events; sport event sustainability; ecological footprint; carbon footprint; wireless sensor networks (WSN); Internet of Things (IoT); Digital Twin; real-time monitoring; decision support; governance and accountability; crowd safety constraints

1 | INTRODUCTION

Fan zones, organized public viewing and celebration areas outside stadia, have become a defining feature of contemporary mega-events. They concentrate large crowds, temporary infrastructures, media screens, concessions, and security operations into dense urban public space, producing an “event within the event” whose operational intensity is comparable to, and sometimes exceeds, the dynamics inside the

stadium footprint (Lee Ludvigsen 2021). Yet, while mega-event sustainability research has expanded rapidly, environmental assessment and decarbonization guidance remain largely stadium- and venue-centric. This creates a blind spot because fan zones have distinctive impact drivers: transport emissions tied to mode share and last-mile access, highly variable electricity loads from large screens, lighting and (in hot climates) cooling, and material and waste flows associated with temporary concessions and single-use packaging, plus neighborhood externalities such as noise and localized air-quality effects (Bae and McCullough 2025, Collins and Cooper 2017). Evidence across sport events consistently indicates that spectator travel often dominates event footprints, underscoring why fan-zone interventions must be designed around mobility behavior and site accessibility rather than only on-site technical

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fixes (Dolf and Teehan 2015, Dosumu et al. 2017, Herold et al. 2024). Fan zones can be read as hybrid “crisis-cell” environments where safety, service continuity, and public legitimacy must be maintained in real time, making decision quality and sensemaking central constraints on any sustainability intervention design (De Vittoris et al. 2023, Sabbah 2024). Despite this importance, the literature still lacks an approach that (1) measures fan-zone impacts with clear system boundaries and repeatable metrics, and (2) links those measurements to operational decisions that can be executed during the event. Reviews note substantial fragmentation in methods, boundary choices, and reporting, which limits comparability across events and prevents cumulative learning (Bae and McCullough 2025). This comparability problem has been repeatedly observed in quantitative assessments of major and mega-sporting events, where methodological choices (system boundaries, travel treatment, and allocation) substantially shape results and the feasibility of benchmarking across event settings (Collins et al. 2007 2009). At the same time, engineering and smart-city research has matured around wireless sensor networks (WSN) and Internet-of-Things (IoT) telemetry for real-time monitoring, and around Digital Twins that synchronize physical systems with simulation models to enable scenario testing and optimization (Mudiyansele and Sellaheewa 2023, Yan et al. 2023, Glebova et al. 2023). More broadly, continuous data infrastructures change what it means to manage and govern complex operations, because they reshape decision contexts, accountability, and strategy by making measurement and intervention more tightly coupled (Constantiou and Kallinikos 2015). However, these technological capabilities have not yet been translated into a coherent, sport-event-specific architecture that closes the loop from real-time measurement to mitigation decisions in fan zones, while respecting safety, experience standards, privacy, and multi-stakeholder governance requirements (Lee Ludvigsen 2021, Mudiyansele and Sellaheewa 2023, Glebova and Madsen 2024). The research problem addressed in this article is therefore the absence of a standardized, operationally actionable framework to quantify, attribute, and mitigate fan-zone ecological impacts in a way that is both comparable across events and usable as real-time decision support. The research question guiding the study is: How can a WSN/IoT-Digital Twin architecture enable standardized measurement and real-time mitigation of fan-zone ecological impacts at mega-events under safety and experience constraints? We answer this question by developing a conceptual framework that integrates (i) a modular sensing layer for flows, energy, waste and externalities, (ii) an attribution layer that converts telemetry and mobility inputs into auditable ecological-footprint metrics, and (iii) a Digital Twin layer that simulates and optimizes pedestrian dynamics, energy loads, and waste logistics through scenario analysis and intervention design (Collins and Cooper 2017, Mudiyansele and Sellaheewa 2023, Glebova 2024). The remainder of the article is structured as follows. The next section reviews scholarship on sport-event environmental impacts and the specific governance and operational features of fan zones, then synthesizes relevant work on ecological-footprint methods (Madsen and Glebova 2025), WSN/IoT monitoring, and Digital Twin decision support. We then develop the proposed WSN/IoT-Digital

Twin framework as a conceptual model, specifying system boundaries, data schemas, core KPIs, and the measurement-to-operations logic that enables mitigation interventions. The final section summarizes theoretical contributions, managerial implications for event organizers and host cities, and outlines limitations and a future research agenda for validation, standardization, and cross-event benchmarking.

2 | LITERATURE REVIEW

2.1 | Sport mega-events, fan zones, and the environmental assessment gap

Sport mega-events are increasingly scrutinized for climate and environmental impacts, and recent syntheses emphasize the primacy of Scope 3 emissions, especially spectator travel, alongside energy and materials/waste impacts that arise from temporary infrastructures and on-site operations (Bae and McCullough 2025). Empirical studies of sport-event footprints repeatedly show that travel can dominate overall emissions, making mode share, trip distance, and access infrastructure pivotal levers for mitigation (Dolf and Teehan 2015, Dosumu et al. 2017, Herold et al. 2024). Yet most assessments focus on stadia or formal venues, leaving fan zones under-specified even though they can attract very large crowds and operate across long daily windows in dense public space. Fan zones also have a distinctive institutional and operational profile because they sit at the intersection of festivity and security, combining crowd-control protocols, policing and safety design, commercial concessions, and media infrastructure in open urban environments (Lee Ludvigsen 2021). This configuration increases the need for measurement systems that do not merely “report” impacts after the event, but support adaptive operations and risk-aware intervention during the event.

2.2 | Ecological-footprint approaches and the need for operational comparability

Ecological-footprint methods and event-focused accounting in tourism and festival contexts provide transparent templates for integrating visitor-driven resource use and for evaluating counterfactual intervention scenarios (Collins and Cooper 2017). Their value lies in boundary clarity, interpretable KPIs, and the possibility of comparing intervention packages across sites and time. However, when imported into sport mega-events, methodological variation remains high, especially regarding system boundaries, treatment of travel, temporal aggregation, and reporting standards (Bae and McCullough 2025). For fan zones, this problem is amplified because the “site” is often a distributed public-space configuration rather than a controlled venue, and because externalities (noise, congestion spillovers) matter to residents and city authorities. What is missing, therefore, is not another footprint estimate per se, but an architecture that generates reproducible, auditable metrics while connecting those metrics to operational levers such as transit

nudges, load shifting, and waste-system redesign (Collins and Cooper 2017, Herold et al. 2024).

2.3 | WSN/IoT telemetry and Digital Twins as decision infrastructure

WSN/IoT research provides mature building blocks for real-time monitoring of flows, resource consumption, and environmental signals. In parallel, Digital Twin research has advanced in smart infrastructure and transportation management, with frameworks emphasizing continuous synchronization between sensor data and simulation models, enabling scenario analysis, optimization, and resilience-oriented planning (Mudiyanselage and Sellaheewa 2023, Yan et al. 2023). In urban mobility and infrastructure, Digital Twins are used to integrate multi-source transport data and test interventions that reduce congestion and emissions, indicating direct relevance to fan-zone transport and crowd dynamics (Yan et al. 2023, Glebova et al. 2023). Yet these developments remain fragmented across domains, and are rarely articulated as a sport-event governance and sustainability solution. Fan zones require a domain-specific integration that treats crowd safety and experience as hard constraints, embeds privacy-by-design, and supports multi-stakeholder governance across event operators, city transport agencies, utilities, security authorities, and vendors (Lee Ludvigsen 2021, Mudiyanselage and Sellaheewa 2023). Consistent with digital governance research, the value of such architectures depends on specifying decision rights, accountability, and control mechanisms for data sharing and algorithmically mediated coordination, rather than assuming that technical integration alone produces usable decision support (Hanisch et al. 2023). City-scale digital twin research similarly emphasizes that governance maturity—covering transparency, stewardship, and institutional readiness—conditions whether twins can be deployed responsibly in public environments and used credibly in operational decision-making (Haraguchi et al. 2024). This also implies responsibility-by-design: monitoring and twin-enabled optimization should be designed with explicit accountability and governance mechanisms rather than treated as purely technical deployments (Chapuis and Guégan 2024, Sahut et al. 2023). Taken together, these literatures justify a “measurement-to-operations” contribution: a fan-zone-specific WSN/IoT–Digital Twin framework that unifies footprint boundaries and KPIs, real-time sensing, and optimization-oriented decision support under event constraints.

3 | CONCEPTUAL MODEL DEVELOPMENT: A WSN/IOT-DIGITAL TWIN FRAMEWORK FOR FAN-ZONE ECOLOGICAL FOOTPRINT MITIGATION

The core novelty developed here is a reference architecture that closes the loop from sensing to attribution to operational optimization. The

framework begins by defining fan-zone system boundaries at three interlocking layers. The mobility boundary captures spectator travel to and from the fan zone, including last-mile access and mode shares, because travel is repeatedly shown to dominate sport-event emissions and is therefore the most material mitigation lever (Dolf and Teehan 2015, Dosumu et al. 2017, Herold et al. 2024). The operations boundary captures on-site electricity loads and their temporal profiles (screens, lighting, sound systems, cooling where relevant), because the timing of loads determines both peak demand and associated marginal emissions in many grids. The materials boundary captures packaging and concession-related flows, waste segregation, contamination rates, collection logistics, and end-of-life pathways, because single-use systems and temporary infrastructures are major sources of waste and embodied impacts in event contexts (Collins and Cooper 2017). Within these boundaries, the sensing layer specifies a modular stack of IoT devices and WSN nodes that capture pedestrian ingress/egress and dwell patterns, micromobility counts, interval-level energy consumption by end-use categories, and localized environmental signals such as noise exposure where regulation and community acceptance are salient. The framework assumes privacy-preserving design principles, including edge de-identification and transparent public signage, so that monitoring remains ethically acceptable in dense public space. Telemetry is time-synchronized to produce interval-level operational indicators that are directly usable for management, not only for post-event reporting. Because the twin's operational usefulness depends on how managers and partners perceive and enact its possibilities, design should also attend to the socio-technical conditions under which digital twin affordances become legible and actionable for users (Osmundsen et al. 2022). The attribution layer converts these indicators into ecological-footprint metrics that are transparent and reproducible. Transport emissions are computed by combining observed or surveyed mode shares with trip-distance distributions and emission factors, explicitly reporting uncertainty bounds because travel footprints are sensitive to assumptions about distance and occupancy (Herold et al. 2024). Energy emissions convert measured kWh into CO₂e using grid-intensity factors that can vary across time; this enables evaluation of mitigation via load shaping and demand response where feasible. Materials and waste are quantified by mass and disposal pathways, with contamination and return rates parameterized to evaluate intervention choices such as reusable systems with deposit-refund logic (Collins and Cooper 2017). The output of this layer is a standardized KPI set (e.g., CO₂e/attendee, kWh/attendee by end-use, diversion rates with contamination bounds, and exposure minutes above noise thresholds) that supports benchmarking across events and host cities. The Digital Twin layer integrates three coupled models that map directly onto fan-zone operational levers while enforcing safety and experience constraints. The pedestrian model (agent-based or queueing-based) is calibrated to observed flows so that mitigation strategies do not compromise crowd safety. The energy model represents controllable loads and scheduling levers (screen luminance profiles, lighting schedules, cooling set-points), enabling scenario analysis that reduces peak load and emissions while

maintaining service quality. The waste-logistics model captures spatially heterogeneous deposition, collection routes, overflow risk, and staffing constraints, enabling evaluation of circular strategies that reduce land-fill diversion shortfalls without creating new congestion bottlenecks. The framework positions optimization as multi-objective, minimizing carbon emissions and waste while respecting safety and experience constraints, which fits the practical governance reality of fan zones as high-visibility, security-sensitive public spaces (Lee Ludvigsen 2021). Finally, the governance layer specifies how multiple stakeholders operationalize thresholds and decision rights. Host-city transport authorities influence mode-shift interventions; utilities enable demand-response strategies; security and safety authorities constrain pedestrian interventions; and vendors control packaging choices and waste-system compliance. The framework therefore treats governance as a design requirement rather than an implementation afterthought, because standardized data schemas, KPI definitions, and accountability mechanisms are necessary for comparability and cumulative learning across events (Bae and McCullough 2025). From an ecosystem perspective, the fan-zone twin becomes a coordination device whose value depends on credible data stewardship and stable collaboration rules across external partners, not only on predictive accuracy (Lissillour and Sahut 2022, Wang 2024). In this sense, the fan-zone system can also be understood as a platform-like socio-technical arrangement, where progress depends on clear conceptual scoping and governance of interfaces, data, and participating actors—issues that digital platform research identifies as central for building cumulative, transferable knowledge (de Reuver et al. 2018). Figure 1 synthesizes our proposed WSN/IoT-Digital Twin framework, showing how real-time sensing, footprint attribution, and Digital Twin simulation/optimization are integrated to translate fan-zone data streams into auditable ecological-impact metrics and operational mitigation decisions under safety and experience constraints.

4 | CONCLUSION

4.1 | Theoretical contributions

This article develops a fan-zone-specific WSN/IoT-Digital Twin framework that links ecological-footprint measurement to operational mitigation under safety and experience constraints. The theoretical contribution is to advance sport-event sustainability research beyond venue-centric measurement by conceptualizing fan zones as operationally distinct, governance-intensive subsystems of mega-events that require integrated mobility-energy-materials accounting. By synthesizing ecological-footprint logic with real-time telemetry and Digital Twin decision infrastructure, the paper also contributes to the broader digital-twin literature by specifying a domain architecture for temporally compressed, crowd-dense public-space operations, extending smart-infrastructure Digital Twin insights into an event sustainability setting (Mudiyansele and Sellahewa 2023, Yan et al. 2023). In addition, the

framework addresses methodological fragmentation identified in sport-event syntheses by proposing boundary clarity and a standardized KPI set that can support cross-event benchmarking and cumulative learning (Bae and McCullough 2025).

4.2 | Managerial Implications

For managers and host-city decision makers, the framework turns decarbonization and resource-efficiency into an operational control problem with measurable levers. The most immediate value is the ability to identify and act on the dominant emissions drivers. Evidence that spectator travel frequently accounts for the largest footprint component implies that fan-zone planning should prioritize transit co-location, last-mile design, and behaviorally informed mode-shift interventions, supported by measurement that verifies impact rather than relying on pledges (Dolf and Teehan 2015, Herold et al. 2024). The framework also supports grid-aware operations by making energy loads visible and schedulable, enabling load shaping strategies that reduce peak demand and emissions without compromising experience quality. In materials and waste, the framework enables credible evaluation of circular strategies (e.g., reusable serviceware), because bin telemetry and logistics modeling make contamination and return rates visible and manageable rather than assumed (Collins and Cooper 2017). At the governance level, the framework clarifies why privacy-by-design, transparent data stewardship, and multi-stakeholder decision rights are prerequisites for deployment in open urban space.

4.3 | Limitations and Future Research

The article is conceptual and therefore has clear limitations. First, it proposes an architecture rather than reporting a validated deployment; empirical implementation in real fan zones is needed to test measurement reliability, sensor validity under dense crowds, and the feasibility of real-time intervention under security constraints. Second, the framework's comparability promise depends on adoption of shared data schemas and boundary definitions; without standardization, cross-event benchmarking will remain difficult. Third, digital twins require calibration and maintenance; future work should examine model drift and the organizational capabilities needed to keep the twin reliable during event operations. Future research should therefore conduct pilot deployments across multiple fan zones and cities, report measurement error and uncertainty bounds transparently, compare intervention effects (e.g., transit nudges, energy scheduling, reusable systems), sport industry 5.0 (Madsen and Glebova 2025), and build shared datasets that enable meta-analyses of what works under different urban forms and climate conditions. These steps would convert the proposed framework from a reference architecture into an evidence-backed sustainability operating system for fan zones. Future empirical work should therefore examine the practice conditions under which such infrastructures become durable governance arrangements—who controls categories, thresholds, and intervention

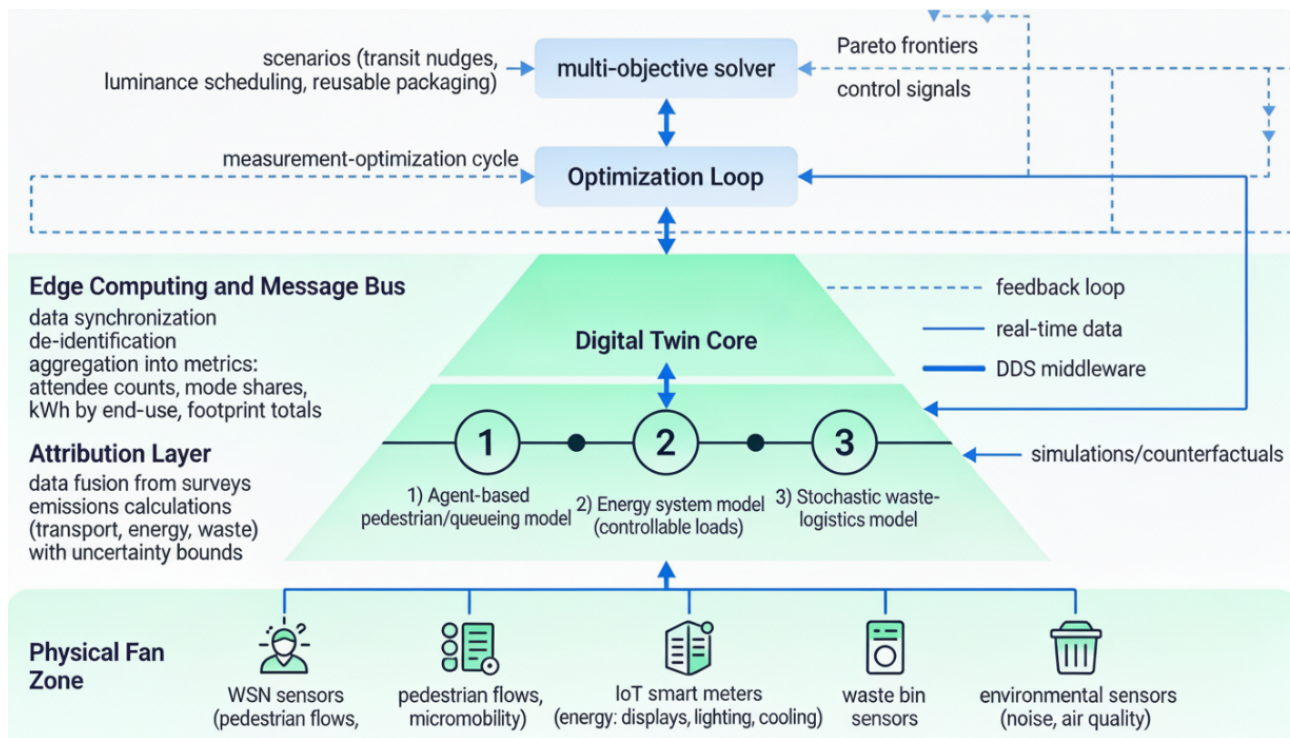


FIGURE 1 WSN/IoT-Digital Twin Framework for Fan Zone Ecological Footprint Measurement and Optimization

rights, and how power and legitimacy shape what is counted and acted upon (Lissillour and Silva 2024, Bahadori and Ramjawan 2025).

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CONFLICT OF INTEREST

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