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SAFETY AND RISK MANAGEMENT THROUGH SMART SOLUTIONS IN SPORTS FACILITIES

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Abstract: This paper analyzes the application of smart technologies in risk prevention and safety management within modern sports facilities. Contemporary stadiums increasingly rely on video analytics, artificial intelligence, RFID/NFC systems, digital ticketing, digital twins, and agent-based simulations to monitor crowd behavior, improve access control, and support real-time operational decision-making. These technologies contribute to the prevention of incidents, optimization of crowd flow, and more effective evacuation planning. The study also highlights the legal, ethical, and cybersecurity challenges related to privacy protection, AI governance, and data security. The findings suggest that the effectiveness of smart safety systems depends on their integration into broader risk management strategies, institutional policies, and operational procedures. Smart technologies are therefore positioned as an important resource for improving safety, sustainability, and management efficiency in contemporary sports infrastructures.

Keywords: smart technologies; sports facilities; risk management; video analytics; digital twins.

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Introduction

Safety and risk management in sports facilities are gaining increasing importance due to the growing size and complexity of sporting events, the heterogeneity of audiences, and the high expectations regarding fan experience. Contemporary practice is shifting from a reactive toward a preventive and "layered" approach, in which technical, organizational, and social measures complement one another so that the failure of one layer does not lead to systemic collapse. This logic is articulated in the recent "Swiss cheese" paradigm of mass gathering safety, which recommends multiple levels of protection—from regulation and planning, through operational control, communication, and incident preparedness, to response and recovery—with the goal of achieving "Vision Zero" (zero tolerance for fatalities). Within this framework, smart solutions such as video analytics, digital/smart ticketing, and crowd management systems represent key technological layers supporting the processes of risk identification, assessment, and mitigation. (Haghani et al., 2023).

Video analytics has experienced a significant leap in reliability over the past decade thanks to deep learning technologies. Systems for crowd density estimation and counting, anomaly detection, and human flow prediction enable the early identification of hazardous situations—critical crowd congestion, counterflows, sudden accelerations, or panic reactions. Comprehensive literature reviews indicate that CNN/Transformer approaches, combined with key practices such as domain adaptation and robust annotation, have reached a level of maturity suitable for operational deployment. However, challenges remain, particularly regarding the transferability of models from laboratory to real-world, variable conditions (different lighting, camera angles, weather conditions), as well as issues of privacy and ethics. For stadium implementation, this implies careful validation on local datasets, cross-integration with fire protection systems, and the evaluation of false alarms as a key KPI. (Wang, Zhou, & Chen, 2025).

At the same time, digital ticketing and RFID/NFC access technologies have become established as the foundation for secure and efficient entry and exit management. Empirical studies in the context of multi-sport events demonstrate that these technologies reduce gate processing time, minimize counterfeiting, enable real-time capacity monitoring, and support the

implementation of health and safety protocols (e.g., contactless entry), while also providing additional value in terms of data integrity and forensic traceability (e.g., combining RFID and blockchain for immutable logs). For facility managers, this means that gate data become a form of "telemetry" for the dynamic allocation of staff, opening and closing corridors, and triaging potential bottlenecks. (Nugraha, Daniel, & Utama, 2021).

The third major pillar consists of crowd management models and tools—from real-time monitoring to evacuation simulations. Agent-based modeling (ABM) enables scenario analysis of spectator distribution, sensitivity testing of exit configurations, and "what-if" testing of operational measures (e.g., flow redirection, phased evacuation, changes in barrier operations). Research conducted on stadium case studies demonstrates that ABM within a "smart city/smart stadium" context can integrate real-world data (IoT, cameras, gates) with simulation models for real-time decision-making—determining the optimal sequence for opening segments, steward positioning, and dynamic crowd routing. In this way, simulations cease to be solely planning tools and become operational "digital twins" of the arena. (Zhang et al., 2018).

The concept of digital twins for sports facilities is increasingly being considered within the broader context of smart sports infrastructure, where simulation models are used not only for evacuation planning but also for long-term facility development. Studies in sports management indicate that digital twins enable the integration of safety, economic, and media-related parameters into a unified decision-support system, thereby contributing to the sustainability and competitiveness of sports arenas.

Experiences from the sports context further emphasize that risk management cannot be purely technological (Stanković, 2025; Jeličić, 2024; Dašić 2018)). —integrated approaches are required that combine infrastructural design, procedures, staff training, and community involvement (e.g., behavioral guidance, clear signage, crisis communication). A systematic review focused on crowd surges and stampedes at sporting events highlights that prevention requires both micro-interventions (redesign of entry/exit areas, removal of "funnel" configurations, control of counterflows) and macro-level measures (coordination with transport systems, decision matrices for area closures), while advanced technologies

are most effective when supporting clearly defined operational protocols. (Ha, 2024).

All of the above naturally fits into the risk management cycle:
(1) Identification – video analytics and gate data indicate dangerous concentrations and anomalies;
(2) Assessment – simulations and historical KPIs (e.g., throughput time, density by zone, false alarm rates) quantify risk;
(3) Mitigation – dynamic flow management, changes in barrier/route configurations, and gate load balancing;
(4) Monitoring and Improvement – post-event analysis based on privacy-by-design principles and clear lines of accountability.

Such a data-driven architecture allows smart solutions to be treated not as isolated "gadgets," but as integral components of a layered safety system aligned with contemporary scientific guidelines. (Haghani et al., 2023; Wang et al., 2025; Zhang et al., 2018; Nugraha et al., 2021; Ha, 2024).

Certainly, the above should not be considered without acknowledging the need for the continuous combination of qualitative and quantitative methods in sports research (Dašić & Vuković, 2024), as well as the application of comprehensive scientific approaches within this field and related disciplines in order to ensure synergistic effects.

Literature Review

From the perspective of sports management, safety management in contemporary sports facilities is increasingly being treated as part of the strategic risk management and corporate responsibility of sports organizations. Research indicates that the digitalization of security systems directly affects the credibility of sports institutions, audience trust, and the sustainability of sporting events, particularly in conditions of intense media exposure and the rapid dissemination of information through digital channels (Dašić et al., 2024).

Contemporary scientific literature suggests that safety and risk management in sports facilities must be approached through an integrated framework that combines infrastructural measures, digital technologies, and ethical-legal standards. Haghani et al. (2023) present the "Swiss cheese model" for crowd management, emphasizing the importance of multiple layers of protection, from planning and prevention to response and post-incident

recovery. This concept is increasingly becoming the foundation for the development of safety protocols in stadiums and major sporting events.

In the field of video analytics, recent reviews highlight the maturity of deep neural networks and transformer architectures for crowd counting, density estimation, and anomaly detection (Wang, Zhou, & Chen, 2025; Hussein, Algamal, & Polat, 2024). These systems enable the early detection of risky situations, such as critical crowd congestion or panic reactions, although challenges remain regarding model transferability to real-world environments and the reduction of false alarms.

At the same time, the development of digital twins for sports facilities enables the integration of simulations and real-time data for the optimization of crowd flow management (Glebova, Ilchenko, & Savin, 2023). These systems connect sensors, cameras, and gate data, creating a digital replica of the arena that supports evacuation scenario analysis and dynamic decision-making.

Research in the field of evacuation simulations demonstrates that agent-based models enable the prediction of bottlenecks and the optimization of exit routes in stadiums, while integration with real-time data allows operational implementation during the event itself (Yang, Lin, & Kuo, 2025). This represents a significant shift compared to traditional planning tools.

Access control systems and digital ticketing technologies (RFID/NFC) have been recognized as key instruments in reducing risks. The work of Nugraha, Daniel, and Utama (2021) demonstrates that these technologies shorten passage time and reduce ticket misuse, while enabling real-time capacity monitoring. More broadly, blockchain technology is also gaining importance in ensuring transparency and data immutability in the sports industry (Principe et al., 2025).

Ethical and legal challenges are particularly emphasized in recent studies analyzing the impact of artificial intelligence on surveillance in sports. Jiapanas (2025) points out that the use of algorithmic video surveillance must comply with the right to privacy and the principle of proportionality. This requires the introduction of transparent mechanisms and independent oversight in order to prevent the excessive use of technologies that may threaten fundamental rights (Stanković & Kostadinović, 2023).

Finally, Ha (2024) emphasizes that risk management must also include spatial interventions such as the redesign of entrances and exits, as well as clear signage and communication with spectators. The combination of these measures with advanced technologies provides the greatest effect in incident prevention.

Recent studies emphasize the growing role of artificial intelligence and IoT-based systems in sports venue security management and crowd control. Smart stadium technologies increasingly rely on predictive analytics, computer vision, and real-time sensor integration in order to monitor crowd density, identify anomalous behavior, and support proactive operational decision-making. Research on smart stadium ecosystems highlights that AI-driven platforms improve situational awareness, optimize resource allocation, and strengthen the operational resilience of sports venues through integrated digital infrastructures (Liang, 2025; Pattarawetwong et al., 2026). Furthermore, the implementation of IoT-enabled crowd monitoring systems allows venue operators to respond more rapidly to potential congestion and safety risks, transforming traditional reactive security models into preventive and data-driven management frameworks.

Another important direction in the literature concerns the sustainability dimension of smart sports infrastructure. Researchers increasingly argue that smart stadium systems should not be viewed solely through the perspective of security and operational management, but also through their contribution to environmental sustainability, energy optimization, and long-term urban development. Studies of contemporary smart stadium models demonstrate that integrated IoT and digital management platforms can significantly reduce energy consumption, improve infrastructure efficiency, and support sustainable governance strategies within broader smart city ecosystems (van Heck, 2021). In addition, recent analyses of sports infrastructure modernization emphasize that smart technologies contribute simultaneously to spectator experience, operational efficiency, and sustainable venue management, positioning sports arenas as multifunctional digital ecosystems connected with wider urban sustainability initiatives (Zhu & Peng, 2024).

Application of Smart Technologies in Risk Prevention in Sports Facilities

Modern sports facilities are increasingly becoming complex cyber-physical systems in which safety and risk management rely heavily on video analytics, predictive modeling of crowd movement, and digital access control systems. In the prevention of incidents, particular importance is given to crowd counting and density estimation models, as well as crowd flow prediction systems, because they enable the timely detection of "hotspots" and preventive interventions in real time (Gao, 2025; Go & Park, 2024).

Video analytics today incorporates deep convolutional and transformer architectures capable of learning both spatial and temporal dependencies, with continuously improving performance under conditions of variable lighting, partial occlusions, and dynamic environments (Dašić, 2023a; Dašić, 2023b). Recent studies demonstrate that hierarchical approaches (e.g., global-local data structures) significantly improve crowd flow prediction across spatial subcategories, which is practically important for different stadium zones with distinct functional purposes (Go & Park, 2024). At the same time, comprehensive reviews indicate that density estimation methods combining contextual scene features and multi-scale convolutions provide more stable metrics in complex scenarios characteristic of sporting events (Gao, 2025).

A key element of risk prevention is the integration of video analytics with access control systems. Data concerning the permeability and reliability of RFID/NFC readers enable the quantification of gate and turnstile capacities, the ranking of configurations according to efficiency, and the synchronization of lane-opening schedules with predicted waves of spectator arrivals. Experimental studies on throughput testing demonstrate how improperly configured reading intervals and an insufficient number of readers escalate into congestion and increased risk at entry checkpoints—findings that are directly transferable to the design of sports facilities (Veľas et al., 2024).

Without perceiving infrastructure solely as the organization of basic facilities and operations (Stanković et al., 2024), digital twins and agent-based simulations are becoming increasingly important for evacuation planning and operational decision-making. Digital twins enable the integration of sensor streams (cameras, counters, ticket readers) with simulation models for scenario analysis and dynamic route optimization in real time; in both urban

and indoor environments, such systems have been shown to support multi-scale simulations and significantly improve evacuation management (Lin et al., 2024). Simultaneously, systematic reviews of ABM approaches in pedestrian evacuations over the last decade identify critical methodological challenges (validation, behavioral realism, crowd communication), but also a clear trend toward integration with machine learning and high-performance computing (HPC), making these systems increasingly applicable to the management of large-scale events (Senanayake et al., 2024).

In summary, practical risk prevention in sports facilities achieves the greatest benefits through the combination of: (a) video analytics for the early detection of dangerous movement patterns; (b) optimized access control based on measured throughput; and (c) digital twins combined with ABM/simulations for scenario-based "what-if" analyses and crowd guidance. Such an architecture enables both operational rules (e.g., dynamic opening/closing of gates, flow redirection) and strategic capacity planning, supported by verifiable, data-driven arguments for decision-making (Gao, 2025; Go & Park, 2024; Lin et al., 2024; Senanayake et al., 2024; Veľas et al., 2024).

Challenges and Perspectives of Integrating Smart Solutions in Sports Infrastructure Management

Although smart solutions bring measurable improvements in safety and security, their integration also introduces technical, legal, and ethical challenges. In the European context, particular emphasis is placed on compliance with the GDPR and the new regulatory framework established by the Artificial Intelligence Act (AI Act): issues concerning legal basis, proportionality, transparency of notification, and the risk of discrimination repeatedly emerge in the context of automated crowd analysis and algorithmic decision-making (Veltmeijer & Gerritsen, 2025). For sports facilities, this means that anonymization/pseudonymization, data minimization, and privacy-by-design principles are not merely recommendations but prerequisites for the legitimate use of video analytics (Veltmeijer & Gerritsen, 2025).

Data governance is becoming critical beyond the scope of video analytics alone, as organizations generate and process large quantities of personal and commercially sensitive information (e.g., biometric access data, fan-related data, athlete telemetry). Recent empirical studies in sport

demonstrate that “effective” organizational protection emerges only through the configuration of multiple factors (e.g., stakeholder trust, institutional support, procedures), requiring interdisciplinary policies and clearly regulated data-flow agreements that define access rights and data-processing purposes (Li & Guo, 2024).

At the same time, the privacy and security of technical platforms must be addressed at every architectural layer. Modern approaches such as distributed analytics and the hashing of sensitive feature vectors demonstrate that it is possible to combine usability with data protection (e.g., locality-sensitive hashing for multimodal sports data fusion), although implementation must be accompanied by clear access-control rules, logging procedures, and deviation-testing mechanisms (Liu et al., 2024). For stadiums, this practically means separating operational data streams (without personal identifiers) from high-risk analytical processes, combined with periodic re-identification testing.

At the infrastructural level, digital twins introduce new values (sensor integration, scenario simulation, decision-support capabilities), but also new risks: synchronization reliability, cybersecurity, and model lifecycle management remain open issues. Comprehensive reviews emphasize that communication protocol standards, data governance, and cyber resilience must be systematically addressed in digital twin projects related to safety and emergency management (Zio & Miqueles, 2024). Consequently, integration plans for sports facilities should include network segmentation (OT/IT), zero-trust principles, and safe-mode degradation procedures in the event of cyber incidents.

Finally, the domain of sporting events is particularly exposed to cyber risks, ranging from attacks on ticketing and access systems to the manipulation of IoT and camera infrastructures. Integrative reviews of the sports-cybersecurity domain indicate a growing scope and diversity of threats, highlighting the need to treat security engineering as an inseparable component of event management (Bongiovanni et al., 2024). In practice, this requires regular risk assessments, red-team exercises, and simulations of incident scenarios involving both physical and digital controls, as well as cross-training among security personnel, IT departments, and operational staff.

Synthesizing the above, the prospects for integrating smart solutions into sports infrastructures are highly favorable; however, success depends on: (1) the formalization of legal frameworks and DPIAs for every data-processing activity; (2) the implementation of technical privacy-by-design principles across all system layers (from cameras/readers to analytics platforms); (3) cyber-resilient digital twins and operational procedures; and (4) continuous risk assessment and model validation under real-world conditions (Veltmeijer & Gerritsen, 2025; Li & Guo, 2024; Liu et al., 2024; Zio & Miqueles, 2024; Bongiovanni et al., 2024).

Viewed as a whole, the implementation of smart safety solutions in sports facilities does not represent an isolated technological process, but rather an interdisciplinary challenge encompassing management, communication, media, and social responsibility. Research within domestic and regional sports contexts emphasizes that the long-term effectiveness of these systems depends on their integration into institutional policies, strategic planning, and safety culture, positioning smart technologies as a key resource of the contemporary sports business.

Conclusion

The research demonstrates that the application of smart technologies in sports facilities represents a crucial step toward improving safety and achieving more effective risk management. Video analytics enables the timely identification of risky situations and anomalies in crowd movement, while smart ticketing and RFID/NFC systems contribute to access control, the reduction of misuse, and improved crowd flow at entry points. Digital twins and agent-based simulations allow sports facilities to be understood as dynamic systems in which crowd flows can be predicted and evacuation scenarios planned in real time.

However, these technologies are not without challenges. Legal and ethical aspects, particularly issues concerning privacy and data security, remain just as important as the technical efficiency of the systems themselves. Furthermore, the integration of smart solutions into sports infrastructures requires clear operational protocols, staff training, and continuous testing under real-world conditions.

In summary, the future development of safety systems in sports facilities does not lie in technology alone, but in its ability to be integrated into

broader frameworks of risk management, where prevention, transparency, and coordination represent the fundamental pillars. In this way, sporting events can remain spaces of positive experience and collective gathering while minimizing risks and protecting all participants.

Conflict of interests

The authors declare no conflict of interest.

Author Contributions

Conceptualization, M.S.; methodology,M.S. and A.C.; software, I.S. ; formal analy-sis, I.S. and M.S; writing-original draft preparation, M.S.; writing-review and editing, I.S. and A.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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