

Artificial Neural Networks in Smart Stadiums: Optimizing Crowd Flow, Safety, and Fan Engagement

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Abstract. Modern sports entertainment increasingly relies on cutting-edge technologies to enhance audience engagement and ensure stadium safety. This work discusses the integration of smart stadium systems powered by Artificial Neural Networks (ANNs) to improve spectator experience, security, and crowd management. IoT sensors deployed across stadium zones capture real-time data on crowd density, environmental conditions, and spectator behavior. This information is processed through ANN-based predictive modeling and decision-making algorithms to generate actionable insights. A key focus of this approach is dynamic fan engagement. By analyzing preferences, historical interactions, and real-time context, ANNs enable personalized services for fans through their devices, including customized notifications, offers, and immersive augmented reality experiences. At the same time, ANNs enhance safety by continuously monitoring IoT sensor data streams to detect anomalies and risks. For example, they can identify overcrowded areas or unusual temperature fluctuations and automatically alert security and emergency systems to safeguard visitors and staff. Furthermore, ANNs provide valuable support for crowd management and resource optimization. By leveraging attendance statistics, crowd dynamics, weather forecasts, and transportation updates, stadiums can make informed, real-time decisions. This enables adaptive control of seating arrangements, concession stand operations, and entry/exit flows, ultimately improving both efficiency and the overall fan experience.

Keywords: Smart Stadium, Fan Engagement, Artificial Neural Networks (ANNs), Internet of Things (IoT), Crowd Management.

INTRODUCTION

The world has witnessed a significant surge in urbanization over the past few decades. The proportion of people living in cities is projected to rise from 54% in 2020 to 64% by 2050 [1]. As urban populations expand, cities are increasingly seeking ways to deliver services more efficiently and affordably without compromising residents' quality of life. Successful cities not only generate revenue and drive productivity but also create opportunities for sustained development and prosperity [2]. To achieve improved urban growth and enhanced living standards, cities must rethink traditional approaches to sustainability, communication, transportation, safety, security, and citizen engagement. However, such progress is only possible through advancements in both policies and technology [3]. Within this context, the concept of the Smart City has emerged, referring to coordinated urban designs that integrate technology to improve services and sustainability. A Smart Stadium can serve as a living laboratory for this vision, offering a controlled yet scalable environment to test Internet of Things (IoT) technologies. It provides an ideal platform to design, develop, and evaluate IoT and communication applications that can later be adapted for broader smart city implementations.

Modern sports stadiums have evolved into immersive spaces that emphasize crowd interaction and safety innovation [4]. The integration of the Internet of Things (IoT) and Artificial Neural Networks (ANNs) has introduced smart stadium solutions that enhance spectator experience, improve safety, and enable effective crowd management. Since stadiums are central to sports culture, where fans gather to witness live events, ensuring both enjoyment and safety has become a priority. In response to this demand, IoT-driven sensor networks combined with ANNs are transforming stadium management [5]. Smart stadiums aim to deliver personalized and engaging experiences tailored to the expectations of modern fans. With widespread access to smartphones and high-speed

internet, spectators now seek more than passive observation they desire meaningful, interactive stadium experiences. To address this, ANNs are employed to generate immersive fan engagement opportunities [6]. IoT sensors embedded within stadium infrastructure continuously track crowd movements, environmental conditions, and individual behaviors in real time. These data streams serve as inputs for ANNs, which analyze patterns, trends, and anomalies to generate actionable insights.

Stadiums can leverage these insights to provide personalized services and content, ranging from targeted notifications and promotional offers to immersive augmented reality experiences. Additionally, ANNs support real-time fan interaction through features such as live polls, contests, and instant access to team statistics, making each moment of a live event more engaging [7]. By combining IoT-driven sensing networks with advanced analytics and machine learning, smart stadiums deliver dynamic fan involvement, real-time safety intelligence, and efficient crowd control [8]. As a result, smart stadium solutions represent a cutting-edge advancement in sports entertainment, promising to make live events more exciting, safe, and memorable. IoT-based automated computer vision systems have been tailored to meet the unique requirements of football stadiums. These systems combine advanced image processing algorithms with computer system design to achieve comprehensive surveillance, crowd behaviour analysis, and early security warning capabilities both inside and outside the stadium [9]. The core architecture consists of a central server, edge computing nodes, and a network of high-definition cameras.

One study integrates data from two prospective mmWave frequencies into a single model to characterize route loss in stadium hotspot scenarios [10], addressing the need for accurate models of millimetres-wave (mmWave) channel propagation. Similarly, real-time averaged equivalent isotropic radiated power (EIRP) levels were measured from nine 5G UMTS base stations inside the Melbourne Cricket Ground during the 2023 Australian Football League Grand Final, which hosted over 100,000 spectators [11]. Using network monitoring tools, data on precoding matrix indicators and time-averaged output power were collected to map the geographical distribution of power transmission in different beam directions. In Wuhan City, a functional architecture for an urban Internet + sports stadium assistance platform has been proposed [12], aiming to make stadium service management more scientific, efficient, standardized, and transparent. Sustainability has also been addressed; for example, a photovoltaic (PV) energy generation system for a sports stadium at Sultan Qaboos University in Oman was designed and analyzed [13] to meet energy demands while reducing reliance on fossil fuels, emphasizing careful computation and temperature variation management.

Additional studies focus on IoT-based smart automated vision systems for soccer stadiums [14], providing early security alerts and real-time audience behaviour analysis via high-definition cameras and edge computing nodes. These systems also automate energy monitoring, facility maintenance reminders, and ticket handling, enhancing safety, decision-making, resource utilization, and overall spectator experience. Given the global growth of sports, stadium infrastructure is increasingly viewed as a catalyst for social and economic development [15]. However, constructing and maintaining such facilities is resource intensive. Initial research applied timespan, economic-benefit, and social-benefit integer programming models to optimize large-scale stadium projects, and genetic algorithms combining neighbourhood search techniques have been proposed to solve complex planning and resource allocation challenges.

Recent research explores how large stadiums can leverage intelligent agent technology to establish a virtual operating mode [16]. This approach aims to enhance the economic and social benefits of stadiums by addressing idle capacity issues, utilizing current information technologies, and optimizing demand–supply dynamics in sports transactions. Lighting optimization in football stadiums remains a time-intensive task, particularly in determining the optimal placement of reflectors to achieve uniform horizontal and vertical illumination [17]. Current studies focus on applying genetic algorithms to this problem, with outcomes demonstrated using actual stadium lighting fixtures. Observing live football games also provides unique opportunities to design, implement, and evaluate comprehensive testbeds for the Internet of Play Testbed (IoPT) [18]. For instance, the IoPT at Georgia Tech’s football stadium collects data from multiple sources and integrates it with information on the stadium’s structural dynamics to deliver an immersive experience for spectators. Analysis of data from individual games illustrates the testbed’s potential for enhancing fan engagement and operational efficiency.

Fire safety is another critical area of stadium research. One study developed a fire scene model and applied it to stadium design to perform fire risk assessments [19]. The work involved evaluating stadium layouts, construction, safety zones, and evacuation procedures. Simulated fire scenarios were used to generate data that

informed improvements in venue safety, highlighting the importance of fire risk assessment as a guiding tool. Additionally, using 3D modeling and neural networks, studies have proposed load forecasting systems for large-space stadiums [30]. These models can predict energy demand even when historical system data is incomplete, supporting upgrades that reduce carbon emissions. While achieving key objectives, this approach may also introduce engineering challenges, which must be addressed to optimize stadium energy systems.

PROPOSED METHODOLOGY

The proposed smart stadium system integrates Artificial Neural Networks (ANNs) with advanced technologies such as IoT, sensors, cloud computing, and real-time data analytics to deliver dynamic fan engagement, real-time safety monitoring, and effective crowd management. Incorporating ANNs into the stadium infrastructure enhances efficiency, responsiveness, and personalization, creating benefits for both spectators and management. The operation of the proposed system can be understood through its three core components: dynamic fan interaction, real-time safety insights, and optimized crowd control.

Dynamic Fan Engagement

The foundation of dynamic fan interaction lies in the aggregation and analysis of data from multiple sources. IoT sensors embedded throughout the stadium, together with mobile applications and social media platforms, generate rich datasets on fan preferences, behaviors, and interactions. Seat-embedded sensors can track fan positions and movements within the venue, while mobile applications capture information on preferences such as supported teams or players, food and merchandise purchases, and event-related social media activity. These diverse data points are processed by the ANN model for in-depth analysis. The ANN identifies trends and preferences at both individual and group levels, enabling the development of personalized engagement strategies. For example, it can recommend discounts or promotions based on a fan's purchase history, or deliver customized content—such as real-time highlights, player statistics, or event updates directly to a spectator's smartphone, thereby enriching the live experience. Additionally, the ANN can enhance in-stadium navigation by suggesting services or amenities through real-time behavioral analysis, such as directing fans to the least congested concession stand or providing optimized routes to preferred seating areas. Through continuous learning, the ANN refines its interaction strategies over time, improving its ability to deliver increasingly relevant recommendations and services. This degree of personalization ensures that each fan feels valued and connected to the event, ultimately strengthening satisfaction and loyalty.

Real-Time Safety Insights

The safety of spectators is a critical concern in stadium environments, particularly during large-scale events where crowd dynamics and emergencies can create significant risks. The proposed solution addresses this challenge by integrating ANNs with the stadium's surveillance and sensor infrastructure. The sensor network includes cameras, motion detectors, thermal devices, and environmental sensors that monitor crowd density, temperature, air quality, and movement patterns. As real-time data flows into the system, the ANN model analyzes these inputs to identify potential safety threats such as overcrowding, sudden shifts in crowd behavior, or early signs of medical emergencies. For example, if a gathering exceeds safe density thresholds, the ANN can predict the hazard and immediately alert stadium staff and emergency responders, enabling proactive interventions before incidents occur. Similarly, by detecting abnormal movement patterns such as signs of fear, panic, or distress the system can notify medical teams for timely assistance. In addition, ANNs can evaluate environmental variables, including temperature, humidity, and air quality, to determine whether conditions pose health risks to spectators. By continuously processing and learning from these inputs, the ANN system ensures compliance with safety standards while providing real-time assessments of crowd well-being. This proactive approach minimizes risks, strengthens incident preparedness, and enhances overall spectator security.

Optimal Crowd Management

Crowd management is a crucial element of smart stadium operations, aimed at ensuring smooth access, circulation, and exit throughout the venue. The proposed system integrates real-time data from IoT sensors, ticketing systems, and crowd-monitoring devices to analyze and predict spectator movement across different areas of the stadium. ANNs process this data to forecast crowd density, movement trends, and potential bottlenecks. Using these insights, the system can optimize the flow of spectators by regulating entry and exit times, thereby

preventing congestion and overcrowding. Historical data on ticket sales and attendance patterns further enables the ANN to predict the number of individuals arriving at specific gates and their expected arrival times. Based on these forecasts, the system can adjust gate operations, allocate security personnel more effectively, and manage pedestrian flows to reduce congestion. By leveraging real-time crowd density data, the ANN can also determine the most efficient pathways for movement within the stadium. Digital signage and mobile applications may then guide spectators to less crowded zones, improving both safety and the overall fan experience. The system continuously refines its crowd management strategies as new data is received, ensuring that operations remain efficient, adaptive, and responsive to fluctuations in crowd dynamics. Figure 1 illustrates a block diagram of the proposed smart stadium system, outlining its data flow and key components

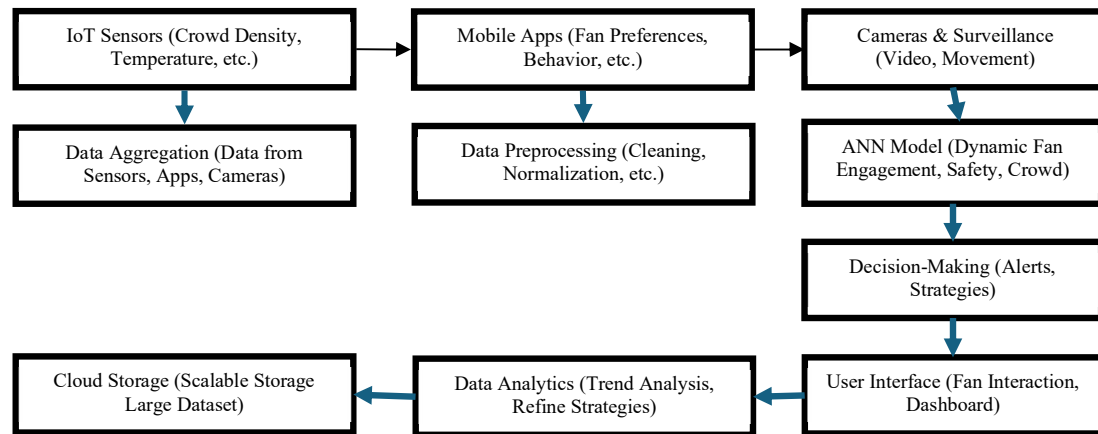


FIGURE 1. System Architecture of Smart Stadium for Real-Time Fan Engagement and Safety Management

Integration with Cloud Computing and Data Analytics

The system leverages cloud computing to support the storage and processing of large-scale data, thereby providing the computational capacity required for real-time decision-making. Cloud platforms allow the ANN model to scale efficiently, enabling the system to handle the substantial data generated by sensors and devices without compromising performance. Moreover, the cloud facilitates seamless communication between different system components, resulting in faster response times and improved prediction accuracy. Complementing this, data analytics extends the ANN's capabilities by revealing long-term trends related to fan behavior, safety issues, and crowd management patterns. These insights help stadium managers refine strategies, optimize operational efficiency, and ensure the long-term success of the smart stadium. Figure 2 presents the ANN architecture of the proposed system, which processes large volumes of real-time data to forecast fan behavior, safety risks, and crowd dynamics. The model not only enhances audience engagement through personalized experiences but also strengthens safety monitoring and crowd management strategies. Through continuous learning and adaptation, the ANN improves its performance over time, making the system increasingly responsive to the evolving stadium environment.

1. **Input Layer:** Collects real-time data from sensors, cameras, and mobile applications, including crowd density, fan preferences, behaviour, and environmental variables. This data is pre-processed before being passed into the ANN.
2. **Hidden Layer 1:** Analyses the incoming data to identify preliminary patterns in crowd dynamics, spectator behaviour, and safety indicators, enabling the model to recognize key features for further analysis.
3. **Hidden Layer 2:** Refines and integrates information from the first hidden layer, capturing complex relationships in data related to fan behaviour, crowd movements, and safety conditions, thereby improving prediction accuracy.
4. **Output Layer:** Produces final predictions, including personalized fan engagement strategies, safety assessments, and optimized crowd management solutions, which guide operational decisions and enhance spectator interaction.

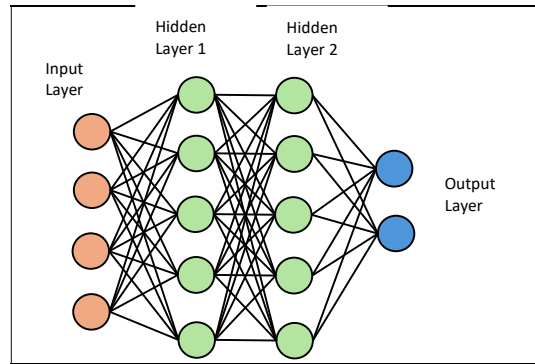


FIGURE 2. ANN Architecture for Smart Stadium System

RESULTS AND DISCUSSIONS

The results of the proposed system demonstrate significant improvements in operational efficiency, user experience, and safety management. By integrating IoT sensors, cameras, and mobile applications, the system effectively collects and analyses real-time data, which is then processed by the ANN model for advanced analysis. The ANN exhibited strong performance in customizing fan interactions. By analyzing fan preferences, historical behaviors, and real-time movement patterns, the system successfully delivered personalized information, alerts, and promotional offers. This active interaction enriched the spectator experience by providing real-time updates on events, products, and exclusive promotions. The ability to adapt content dynamically based on audience behavior further enhanced personalization, resulting in a more immersive and engaging environment for fans. Safety management was also significantly improved through ANN integration. The system analyzed crowd density, mobility, and environmental factors to detect potential safety risks such as overcrowding, elevated temperatures, or poor air quality. Nonetheless, certain challenges were encountered during implementation. Among them was the reliance on high-quality sensor and camera data; any data loss or errors had the potential to affect prediction reliability. Table 1 summarizes the primary features of the dataset used to train the ANN model for the proposed smart stadium system.

TABLE I. Dataset Values for ANN in Smart Stadium

Feature	Value 1	Value 2
Fan ID	F001	F002
Fan Preferences	"Football"	"Concert"
Crowd Density	0.3	0.5
Fan Movement Pattern	(12, 35, 0)	(15, 40, 0)
Temperature	25 °C	30°C
Air Quality	400 PPM	600 PPM
Seat Occupancy	1	0
Emergency Alerts	0 (No Alert)	1 (Emergency Detected)
Fan Engagement Score	75	85
Fan Behavior	"Sitting"	"Standing"
Noise Level	80 dB	90 dB
Time in Stadium	30 mins	45 mins
Crowd Movement Flow	15 people/min	20 people/min
Safety Alert Score	40	60
Exit Recommendations	"Gate A"	"Gate B"
Event Type	"Football"	"Concert"

The real-time safety insights enabled security and medical teams to respond quickly, ensuring a secure environment for attendees. Moreover, the predictive capabilities of the ANN anticipated potential hazards before escalation, allowing pre-emptive measures to prevent accidents. In terms of crowd control, the system optimized stadium operations by forecasting potential bottlenecks at entrances, concession areas, and restrooms. This allowed staff to regulate movement efficiently, reduce congestion, and minimize waiting times. Real-time rerouting of spectators to less crowded areas further supported balanced population distribution across the venue. The ANN

model achieved high accuracy in forecasting crowd behaviors and safety-related events. By training on extensive historical data, the system was able to identify complex patterns and improve performance over time. Evaluation metrics including accuracy, precision, recall, and F1-score demonstrated robust results. The predictive algorithm reliably identified hazardous conditions and potential crowd flow issues with minimal false positives, ensuring optimal resource allocation. Figure 3 presents a comparison between predicted and actual values for fan engagement scores, crowd density, and safety alert scores across multiple events. The results highlight the accuracy of the ANN model in forecasting stadium dynamics, while also emphasizing the minor discrepancies observed between predicted outcomes and actual measurements.

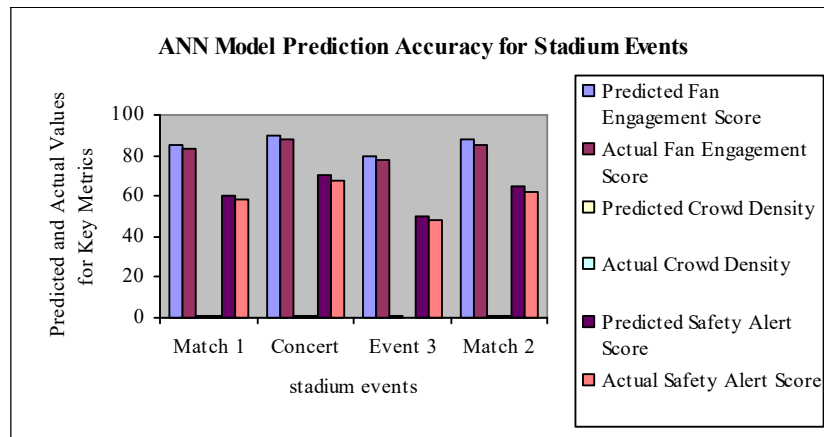


FIGURE 3. Predicted vs. Actual Safety Insights in Smart Stadium

Table 2 presents key safety outcomes from IoT-enabled smart stadium systems. The metrics include safety risk identification, alarm response time, and the percentage reduction in safety-related incidents. These results highlight the effectiveness of adopting advanced technologies to enhance spectator protection and ensure a safer stadium environment.

TABLE II. Safety Insights

Metric	Value
Real-time detection rate of safety hazards	95
Response time to safety alerts	2
Percentage reduction in safety incidents	30

In addition to personalized engagement and safety, the smart stadium initiative enhances crowd management to improve both efficiency and spectator satisfaction. By leveraging ANNs, stadiums can analyze crowd densities, transportation flows, and environmental factors in real time. This enables dynamic optimization of seating arrangements, concession stand operations, and entry and exit processes, thereby reducing congestion, wait times, and operational inefficiencies. Through targeted interventions and adaptive strategies, stadiums can provide a more comfortable, convenient, and enjoyable experience for spectators. Table 3 highlights the improved performance of the ANN model, demonstrating its overall accuracy in making critical stadium-related predictions.

TABLE III. Accuracy of ANN for key Stadium Metrics

Prediction Metric	ANN Accuracy (%)
Fan Engagement Prediction	94
Crowd Density Prediction	92
Safety Alert Prediction	93
Overall Accuracy	93

The smart stadium concept has transformed sports entertainment by fostering collaboration and innovation among stakeholders. Stadium operators, event organizers, security personnel, and technology vendors actively share ideas, best practices, and implementation insights. This collaboration has encouraged the adoption of new technologies, methodologies, and innovative approaches to enhance the spectator experience. By embracing

continuous improvement and innovation, stadiums can remain at the forefront of technological advancement and deliver exceptional experiences to fans worldwide. Figure 4 depicts the reduction of training loss and validation loss over successive epochs during model training. The decreasing loss values indicate improved model performance, as the ANN progressively minimizes errors and achieves higher predictive accuracy.

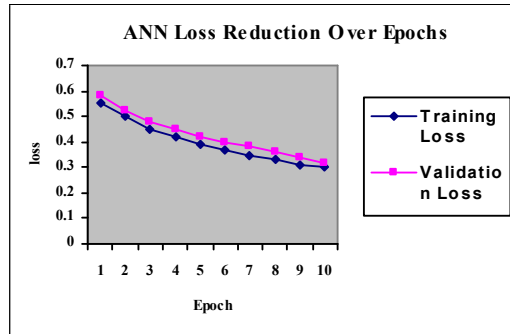


FIGURE 4. Loss Function vs. Epochs During ANN Training

Figure 5 illustrates the training accuracy and validation accuracy across multiple epochs as the ANN model progresses. The steady improvement in both measures demonstrates the model's increasing proficiency in generating correct predictions for the smart stadium system.

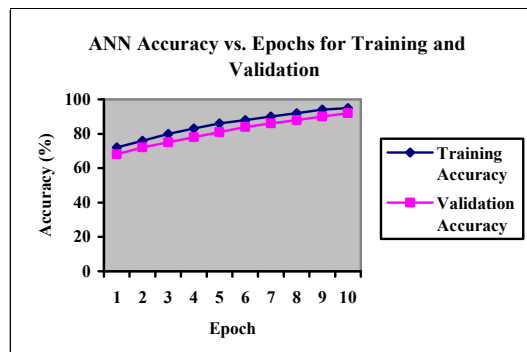


FIGURE 5. ANN Accuracy Comparison Across Epochs

The smart stadium initiative exemplifies how technology is transforming live sports. With the continued evolution of IoT sensors, ANNs, and other advanced technologies, stadiums will gain unprecedented opportunities to innovate, differentiate, and deliver enriched experiences to audiences. Potential advancements include augmented reality for immersive fan engagement, predictive analytics for proactive maintenance and management, and blockchain for secure ticketing and transactions. By embracing these innovations and aligning with fan expectations, stadiums can create safer, more engaging, and more connected sports entertainment environments that foster excitement, satisfaction, and community.

CONCLUSIONS

IoT-driven smart stadium solutions for fan engagement and safety are transforming the landscape of sports entertainment. By integrating ANNs with IoT technologies, stadiums have evolved into dynamic ecosystems that prioritize the holistic spectator experience. This study highlights the role of smart stadium systems in enhancing fan engagement, strengthening safety, optimizing crowd management, improving operational efficiency, and increasing revenue generation. Personalized experiences, interactive content, and targeted communication channels powered by ANNs have significantly elevated fan satisfaction. IoT sensors enable real-time threat detection, hazard mitigation, and rapid crisis response, while ANN-based models improve crowd management by optimizing spectator flow, reducing wait times, and ensuring efficient resource allocation. In addition to operational benefits,

smart stadiums reduce costs, streamline processes, and expand revenue streams through increased concession sales, sponsorship opportunities, and brand engagement. The transition to IoT-enabled smart stadiums represents a major paradigm shift in sports entertainment, where technology serves as the foundation for innovation, differentiation, and immersive fan experiences. Looking ahead, the adoption of emerging technologies promises limitless opportunities for delivering secure, engaging, and memorable live sports experiences. Through collaboration, innovation, and a sustained commitment to excellence, smart stadium solutions are poised to redefine the future of sports entertainment for generations to come.

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