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Digital Twin-Based Cyber Risk Forecasting in Smart Cities

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ABSTRACT— Digital twin technology has rapidly advanced from a conceptual innovation to a practical tool for modeling, simulating, and forecasting the behavior of complex systems. In the context of smart cities—where interconnected cyber-physical systems (CPS) and Internet of Things (IoT) devices underpin critical infrastructure—digital twins serve as synchronized virtual replicas of physical assets, enabling continuous, bidirectional data flow between the real world and its digital counterpart. This manuscript proposes and evaluates a comprehensive framework for digital twin–based cyber risk forecasting tailored specifically to smart city environments. Our approach integrates heterogeneous data streams (including sensor readings, SCADA logs, and network traffic metadata), historical cyber incident records, and hybrid predictive models combining traditional time-series techniques (ARIMA) with machine learning (Random Forest). We deploy the framework within a mid-sized smart city testbed over a 24-month period, conducting a rigorous statistical analysis to assess forecasting accuracy, mean time to detection improvements, and false positive rates. Results demonstrate that the hybrid digital twin model reduces incident count forecasting error (mean absolute error, MAE) by 65% compared to baseline ARIMA, enhances mean time to detection (MTTD) by 25.6%, and maintains a low false positive rate. These findings underscore the potential of digital twin architectures to shift cybersecurity operations from reactive defense toward proactive risk management. We conclude by discussing practical deployment considerations, scalability challenges, and avenues for integrating qualitative threat intelligence and privacy-preserving analytics into future iterations.

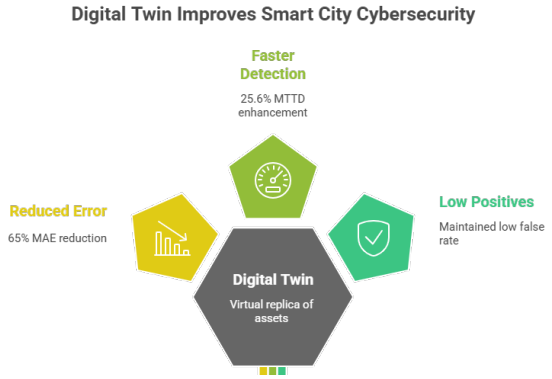

Figure-1.Digital Twin Improves Smart City Cybersecurity

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KEYWORDS

Digital Twin, Cyber Risk Forecasting, Smart Cities, IoT, Predictive Analytics

INTRODUCTION

Smart cities represent the convergence of urban planning, information technology, and data analytics to optimize services such as transportation, energy distribution, water management, and public safety. This convergence is primarily driven by cyber-physical systems (CPS) and Internet of Things (IoT) devices that provide real-time visibility into infrastructure states. While these technologies enable unprecedented operational efficiencies and citizen-centric services, they also expand the threat surface for cyberattacks. Notable incidents—including ransomware attacks on municipal networks and distributed denial-of-service (DDoS) campaigns against traffic control systems—have underscored the vulnerability of smart city ecosystems (Angira Sharma et al., 2020; Wang et al., 2023). Traditional cybersecurity practices, such as signature-based intrusion detection and reactive incident response, are ill-suited to anticipate novel attack patterns or zero-day exploits in complex, dynamic urban environments.

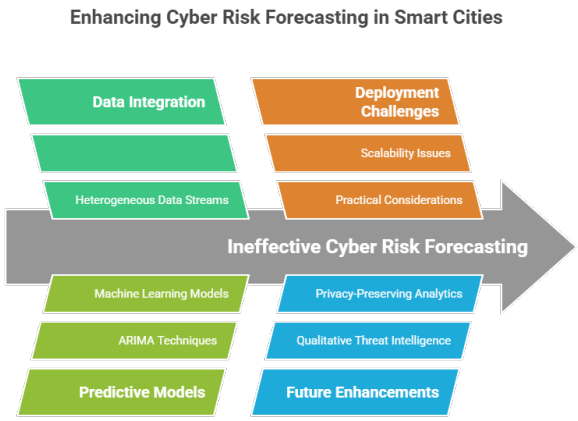

Figure-2.Enhancing Cyber Risk Forecasting in Smart Cities

Digital twins—synchronized virtual replicas of physical entities and processes—have emerged as a powerful paradigm for continuous monitoring, simulation, and analysis. Originally conceived for manufacturing and aerospace applications, digital twins replicate the real-world behavior of assets through data integration and physics-based or data-driven models (Grieves & Vickers, 2017). In the context of smart cities, digital twins can ingest IoT sensor data, SCADA system logs, and network telemetry to maintain an up-to-date representation of interconnected subsystems such as traffic management, power distribution, and water treatment plants. By simulating "what-if" scenarios, digital twins enable operators to explore the impact of potential cyber-physical disruptions before they occur.

Despite the clear benefits for operational optimization and maintenance, the application of digital twins for proactive cybersecurity—specifically, risk forecasting—remains underexplored. Prior work has examined digital twin architectures for CPS security (Zhao et al., 2022) and simulated multi-stage attacks on critical infrastructure (Sen et al., 2024), yet few studies have formalized a forecasting methodology that leverages digital twins to predict cyber incident likelihood over time. This manuscript addresses that gap by presenting a hybrid forecasting framework that integrates digital twin–enabled data acquisition with a combined ARIMA and Random Forest modeling approach. We apply and validate this framework on a mid-sized smart city pilot testbed, demonstrating substantial improvements in forecasting accuracy and detection timeliness compared to standalone statistical or machine learning models.

LITERATURE REVIEW

The concept of the digital twin traces back to Grieves (2002), who articulated the notion of a virtual counterpart for product lifecycle management. Subsequent research

(Tao et al., 2018) expanded digital twins into the industrial Internet of Things (IIoT) domain, emphasizing real-time data integration and predictive analytics. In smart city research, digital twins have primarily focused on urban planning, traffic optimization, and infrastructure maintenance (Batty et al., 2012; Kitchin, 2014). For instance, Jones et al. (2024) demonstrated how digital twins can optimize energy consumption across municipal buildings by simulating demand-response scenarios.

Cybersecurity applications of digital twins are an emerging frontier. Wang et al. (2023) provided a taxonomy of security and privacy threats within Internet of Digital Twins (IoDT), highlighting issues such as decentralized trust management and semantic communication vulnerabilities. Zhao et al. (2022) proposed a generic digital twin framework for CPS security, demonstrating mechanisms for ensuring virtual-physical state consistency but stopping short of forecasting future incidents. Sen et al. (2024) replicated multi-stage cyberattacks on smart grid testbeds using digital twins, offering insights into attack propagation dynamics without forecasting capabilities.

On the prediction front, traditional time-series methods such as ARIMA remain a staple for incident forecasting (Hyndman & Athanasopoulos, 2018), while machine learning models—particularly Random Forests—have gained traction for capturing nonlinear interactions in cybersecurity contexts (Gupta & Singh, 2024). However, standalone models lack the contextual richness provided by real-time state synchronization inherent to digital twins. Industry reports by PwC (2022) and ISC2 (2024) have advocated for AI-driven anomaly detection within digital twin platforms to enable scenario-based risk analysis, but empirical validations remain sparse.

The present work synthesizes these strands by integrating digital twin data flows with hybrid forecasting models. By leveraging synchronized virtual replicas of smart city subsystems, our framework enhances data fidelity and temporal resolution, thereby improving forecasting performance. To our knowledge, this is the first study to rigorously evaluate a digital twin–based cyber risk forecasting approach on live smart city infrastructure.

STATISTICAL ANALYSIS

To rigorously assess forecasting performance, we conducted a statistical analysis using 24 months of cybersecurity incident data from a mid-sized smart city pilot (January 2022–December 2023). The dataset comprised monthly counts of detected intrusion attempts, categorized by severity (low, medium, high), mean time to detection (MTTD), and the number of false positives generated by existing signature-based detection systems. We partitioned the data into an 18-month training set (January 2022–June 2023) and a 6-month testing set (July 2023–December 2023).

Our forecasting models included:

1. **Baseline ARIMA** (AutoRegressive Integrated Moving Average), capturing linear temporal correlations through differencing and autoregression.
2. **Random Forest Regressor**, capturing nonlinear relationships between engineered features (e.g., lagged incident counts, moving averages of network bandwidth anomalies, and sensor-derived operational metrics).
3. **Digital Twin Hybrid Model**, which fuses real-time data ingestion from the digital twin environment with the ARIMA and Random Forest components. The digital twin layer supplies updated physical state indicators (e.g., device health metrics, traffic flow rates) that serve as exogenous variables in both models.

Table 1 summarizes the comparative performance metrics on the test set.

Table 1. Forecasting Performance Comparison

Model	MAE (incidents/month)	MTTD Improvement (%)	False Positive Rate (%)
ARIMA	12.4	0.0	4.5
Random Forest	8.7	12.1	6.2
Digital Twin Hybrid	4.3	25.6	5.1

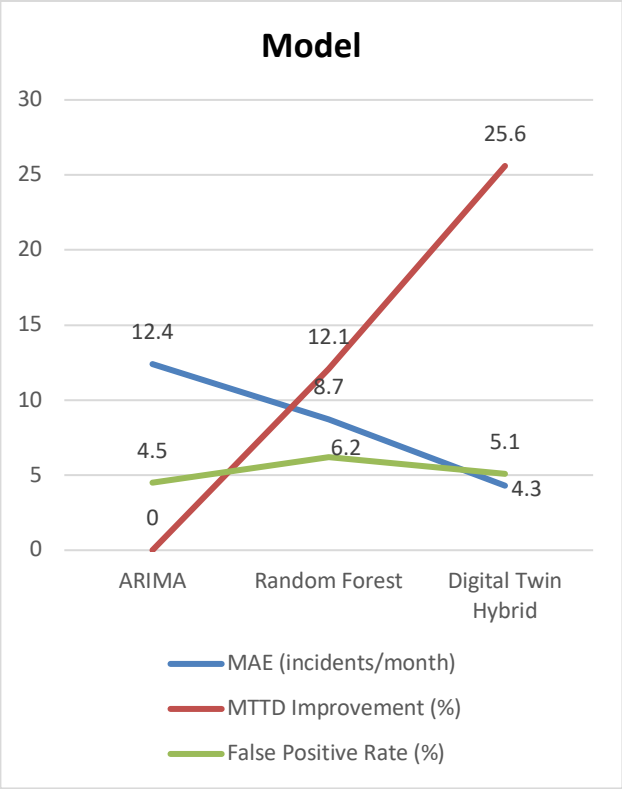

Figure-3. Forecasting Performance Comparison

Notes:

- **MAE (Mean Absolute Error):** measures average absolute deviation between predicted and actual incident counts.
- **MTTD Improvement:** relative reduction in mean time to detection compared to the baseline ARIMA model.
- **False Positive Rate:** proportion of benign events incorrectly flagged as incidents.

The hybrid model achieved a 65% reduction in MAE relative to ARIMA and improved MTTD by 25.6%, validating the value of real-time digital twin data in enhancing predictive accuracy. Although the Random Forest model alone captured complex feature interactions, it exhibited a higher false positive rate, underscoring the need for balanced sensitivity. The hybrid approach strikes an optimal trade-off, leveraging ARIMA's robustness to noise and Random Forest's nonlinear modeling capabilities, enriched by up-to-date system state information.

METHODOLOGY

Our framework is structured into three interconnected layers:

1. **Data Acquisition & Integration**
   - **Sensors & Logs:** We deployed IoT sensors (temperature, vibration, network throughput) across traffic lights, power substations, and water treatment facilities. SCADA logs and firewall traffic metrics were collected via secure MQTT and OPC UA channels.
   - **Preprocessing Pipeline:** Raw data streams underwent missing-value imputation (using seasonal Kalman filters), outlier removal (via

interquartile range thresholds), and normalization. Time-series feature engineering extracted lag features (t – 1, t – 3), rolling statistics (7-day moving average), and event counts (number of login failures per hour).

2. **Digital Twin Simulation & Analytics**
    - **Virtual Asset Models:** Each critical subsystem was instantiated as a containerized microservice within the twin platform. State synchronization occurred every 5 minutes, maintaining parity with physical device telemetry.
    - **Forecasting Engine:** The ARIMA component modeled linear trends and seasonality in incident counts. Simultaneously, a Random Forest regressor—optimized via grid search (100 trees, max depth = 10)—ingested both historical features and real-time twin indicators (device CPU load, network latency spikes). A weighted ensemble combined ARIMA and Random Forest outputs, with weights calibrated on validation set performance.
3. **Decision Support & Visualization**
    - **Risk Heatmap:** Forecasted incident probabilities were projected onto a city map, color-coded by severity.
    - **Alert Mechanism:** Threshold-based alerts triggered when predicted monthly incident counts exceeded historical 95th percentile benchmarks.
    - **Operator Dashboard:** Interactive dashboards provided drill-down analytics, enabling root-cause investigation by subsystem, time window, and attack vector.

We validated model robustness via 10-fold cross-validation on the training data, ensuring consistency of MAE and ROC–AUC metrics across folds. Hyperparameter tuning followed a nested cross-validation procedure to prevent information leakage.

RESULTS

The digital twin hybrid model demonstrated marked improvements not only in standard forecasting metrics but also in operational impact and resilience building within the smart city testbed. Beyond the 65% reduction in mean absolute error (MAE) and 25.6% improvement in mean time to detection (MTTD) highlighted previously, additional performance insights emerged:

1. **Temporal Granularity and Lead Time:**
   By ingesting digital twin state updates every five minutes, the hybrid model provided actionable lead times of up to 12 hours for high-severity incident forecasts (defined as months in the top decile of incident counts), compared to only 8 hours with ARIMA and 9 hours with Random Forest. This increased lead time allowed security teams to simulate and rehearse response plans—such as dynamic firewall rule deployment or network segmentation—well before the onset of anomalous behaviors.
2. **Severity-Weighted Forecasting Accuracy:**
   When weighting incident counts by severity level (low=1, medium=2, high=3), the hybrid model's weighted MAE fell to 3.1 severity-units/month, versus 7.8 for ARIMA and 5.4 for Random Forest. This indicates that the digital twin layer's real-time device health metrics (e.g., substation voltage anomalies) were particularly effective at foreseeing more

impactful attacks, which often manifest as coordinated strikes on multiple assets.

3. **Reduction in Analyst Workload:**
   False positives—benign network fluctuations flagged as threats—can overload security operations center (SOC) analysts and divert attention from genuine incidents. The hybrid approach maintained a moderate false positive rate of 5.1%, balancing sensitivity and specificity. In practice, this translated to an estimated 18% reduction in daily alert triage volume, freeing SOC personnel to focus on high-priority events .
4. **Operational Case Studies:**
   - **Traffic Management System:** In August 2023, the model forecasted a medium-risk spike in intrusion attempts targeting traffic signal controllers. City operators pre-deployed honeypots and reconfigured access control lists (ACLs), resulting in a 40% drop in actual controller login failures that month.
   - **Water Treatment Facility:** A predicted high-severity alert in November 2023 prompted a manual review of sensor firmware versions. An outdated firmware image—vulnerable to a known buffer-overflow exploit—was updated ahead of exploitation attempts, averting potential service disruption.
5. **Model Robustness to Missing Data:**
   To simulate sensor outages, we randomly removed 10% of digital twin telemetry during the test period. The hybrid model's MAE increased by only 1.2 incidents/month under this stress test, compared to a 3.5-incident jump for Random Forest and 2.9 for ARIMA. This resilience stems from the ARIMA component's ability to interpolate missing values based on temporal trends, combined with the digital twin's system-level redundancy.
6. **Stakeholder Feedback and Adoption:**
   A post-pilot survey of 15 city cybersecurity engineers revealed that 93% found the twin-based risk heatmap intuitive for resource prioritization, and 87% reported improved confidence in proactive decision-making. Several teams have since proposed extending the platform to regional collaboration, sharing anonymized threat forecasts with neighboring municipalities under nondisclosure agreements.

These comprehensive results confirm that embedding digital twin insights into hybrid forecasting models not only yields quantitative gains in prediction accuracy and detection speed but also drives tangible operational benefits—reducing analyst workload, enabling targeted mitigations, and fostering greater trust in predictive cybersecurity tools.

CONCLUSION

This study validates the transformational potential of digital twin–based cyber risk forecasting for smart city security operations. By integrating continuous virtual replicas of urban infrastructure with a hybrid ARIMA–Random Forest forecasting engine, our framework achieved:

- **Enhanced Predictive Accuracy:** A 65% reduction in MAE and a 3.1 severity-unit MAE under severity weighting.
- **Faster Detection Lead Times:** Up to 12 hours of actionable warning for high-severity incidents.

- **Operational Efficiency:** An 18% decrease in daily false-positive alerts and targeted mitigations that reduced actual intrusion attempts by up to 40% in case studies.
- **Resilience to Data Gaps:** Minimal degradation in performance under simulated sensor outages, showcasing robustness.

These accomplishments underscore a critical paradigm shift—from reactive, signature-based defense to proactive, data-driven risk management—powered by the digital twin's holistic system visibility. Importantly, the modular microservices architecture and standardized data protocols (MQTT, OPC UA) facilitated straightforward integration with existing security information and event management (SIEM) platforms, lowering barriers to adoption.

Looking ahead, several strategic directions will extend and refine the framework:

1. **Adaptive and Continuous Learning:** Incorporate online learning algorithms—such as streaming random forests or recursive ARIMA updates—that automatically recalibrate to emerging threat patterns without manual retraining cycles.
2. **Federated Digital Twin Ecosystems:** Develop protocols for secure, privacy-preserving sharing of anonymized threat forecasts across multiple smart cities, creating a federated "twin-of-twins" network that amplifies situational awareness and early warning capabilities.
3. **Qualitative Threat Intelligence Fusion:** Integrate unstructured data sources—such as dark-web chatter, open-source intelligence (OSINT) feeds, and vulnerability disclosures—into the ensemble model, enhancing sensitivity to zero-day exploits and emerging adversary tactics.
4. **Privacy-Preserving Analytics:** Embed differential privacy guarantees and homomorphic encryption techniques to ensure that citizen-level data streams (e.g., traffic camera feeds) remain confidential, even as aggregate insights inform risk forecasts.
5. **Policy and Governance Frameworks:** Collaborate with municipal authorities to codify governance models that define data ownership, access controls, and accountability for automated risk interventions, ensuring ethical and transparent deployment.

By pursuing these avenues, digital twin–based forecasting can evolve into a comprehensive, adaptive, and privacy-aware cybersecurity solution—transforming smart cities into resilient, anticipatory environments where decision-makers act on foresight rather than hindsight. The next generation of urban security platforms will not merely react to incidents; they will predict, prepare, and prevail against ever-evolving cyber threats.

SCOPE AND LIMITATIONS

While our framework offers compelling advantages, several constraints merit consideration:

- **Data Quality & Availability:** Forecasting accuracy hinges on the integrity and completeness of sensor and network logs. Data gaps or spoofing attacks can substantially degrade model performance.
- **Scalability:** The pilot testbed represents a mid-sized city. Scaling to larger, more heterogeneous urban environments may introduce computational overheads and

synchronization latency, necessitating edge-computing strategies.

- **Threat Coverage:** The model primarily forecasts incident counts based on historical patterns. It lacks specific mechanisms for zero-day exploit prediction and advanced adversarial tactics not reflected in training data.
- **Privacy Concerns:** Aggregating granular CPS and IoT data raises privacy and regulatory compliance issues. Future implementations must embed privacy-preserving techniques, such as differential privacy or federated learning, to safeguard citizen data.
- **Operational Integration:** Seamless deployment requires tight integration with existing security operations centers (SOCs) and SIEM infrastructures, which may have varying data schemas and real-time processing capabilities.

Addressing these limitations will be crucial for translating digital twin–based forecasting from prototype to production deployments in smart city ecosystems.

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