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Implementing Digital Twins for Real-Time Library Operations Monitoring

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***Abstract* - Increased user expectations for intelligent systems fuel enhanced digitization of daily activities in library systems. We propose a new framework RT-LTM, Real-Time Library Twin Monitoring, which aims to utilize Digital Twins for real-time monitoring, predictive maintenance, and tailored service optimization in library spaces. RT-LTM framework designs a virtual model of library assets such as books, RFID-tagged materials, HVAC systems, and previous behavior analytics to achieve real-time synchronization of physical and virtual systems. The architecture integrates IoT sensors, edge-cloud computing, and AI analytics for real-time monitoring of spatial efficiency, resource consumption, and maintenance forecasting. A university library case study demonstrates the active library's real-time monitoring efficacy, resource access, energy use, and user satisfaction. The results highlight the outstanding impact of Digital Twin technology in contemporary library systems and services management.**

***Keywords:* RT-LTM, Digital Twin, Smart Library, IoT Real-Time Monitoring, Automation in the Library, Predictive Maintenance, Resource Use Optimization, User Behavior Analytics, Digital Library Transformation, Library Management Software**

I. INTRODUCTION

1.1 Background and Motivation

Recent years have seen a dramatic shift in how industries operate due to the rapid acceleration of transformation in a digital capacity. This impacts even the traditionally physical realms such as libraries (Abisoye, 2023). As the chief operators of distributing information, libraries now need to leverage smart technologies that facilitate real-time analytics, boost artificial intelligence, enhance the level of service, and drive the optimal use of resources. In this regard, the idea of Digital Twin (DT) as a promising innovation enables the creation of real-time digital copies of physical spaces that can be monitored, simulated, and enhanced dynamically.

1.2 Concept of Digital Twins in Library Environments

A digital twin assimilates current sensor data with relevant analytics and models driven by artificial intelligence to capture and reflect the up-to-the-moment condition, function, and behavioral dynamics of physical assets within a virtual counterpart (Pregnolato et al., 2022). Within the context of library systems, this entails monitoring critical functions like circulation of books, active and passive occupancy counting, and monitoring environmental and structural systems for condition and performance—allowing for anticipatory maintenance and improved interaction with users. Achieving digital twins, within the context of smart infrastructure, also aids in larger sustainability and efficiency objectives, for instance in schools. (Sharipov et al., 2024) highlight how digital tools can be leveraged to enhance educational engagement and environmental awareness—an approach that aligns with the use of digital twins to promote interactive and sustainable learning environments in modern libraries.

1.3 Gap in Existing Research

The smart campuses, automated laboratories, and energy-efficient building systems have recently been explored using digital twin frameworks (Alkhateeb et al., 2023; Meschini et al., 2022). Nonetheless, their models have yet to be fully developed and implemented within the context of library systems. This study seeks to bridge this gap by introducing RT-LTM (Real-Time Library Twin Monitoring)—a new framework which is aimed at applying digital twin concepts for the proactive monitoring of library operations and dynamic management of library resources.

1.4 Proposed RT-LTM Architecture Overview

The RT-LTM framework allows smooth unification of physical library assets and their digital equivalents with IoT-based sensing, AI-based analysis, and a cloud-continuous system digital interface organized in a three-tier architecture. The system collects data regarding environmental conditions of the library space (air quality, noise levels, and devices uptime), library assets usage (shelf status), and user activities (foot traffic and interaction), and processes these with predictive models to simulate library operations and provide forecasts. This configuration empowers library staff to make proactive interventions and aids in automating manual activities such as illumination, climate control, or servicing routines.

1.5 Smart Operations and Sustainability Goals

As libraries evolve into more dynamic environments which combine collaboration, information services, and digitized resources, the dated practices of operations no longer work. Outdated practices of manual inventory, delayed maintenance, and inefficient use of space lapse services and waste resources. The RT-LTM model resolves these issues by providing real-time control and visibility of core library operations. Furthermore, the capability of the system to simulate user and operational anomaly behavior enables proactive mitigation of disruptions, optimizing uptime and un-interrupted service delivery. From a sustainability perspective, smart libraries utilizing digital twin frameworks enhance institutional sustainability goals. RT-LTM aligns energy consumption with real-time demand and minimizes idle resource utilization, thus supporting the self-defined sustainability goals dictated by green computing. Furthermore, advanced analytics utilizing AI for behavioral observation allows space and crowd control, thus improving the comfort and accessibility in the post-pandemic world while adhering to socially distanced norms (Mahariya et al., 2023).

1.6 Personalization and Digital Inclusion

Equally important is the system's ability to customize the user experience through RT-LTM. This system can recommend optimal visit times, customized digital alerts, and provide navigational assistance through voice commands. These features are in alignment with the growing user-oriented architectural changes in library and information systems and are likely to improve user satisfaction and participation among the various user categories, that is, students, scholars, as well as the physically handicapped (Ponnusamy et al., 2024).

1.7 Challenges and Research Contribution

Although promising, the adoption of digital twins in libraries comes with difficulties, such as interfacing with existing older systems, data privacy and security issues, and the need for a considerable initial investment. This study underscores, within the RT-LTM framework, focus on scalable architecture, modular deployment, and secure data governance to comply with institutional IT frameworks and integrated transformation plans.

1.8 Summary

In conclusion, the RT-LTM model articulated within this paper seeks to reconceptualize the operation of a library with real-time intelligent supervision, adaptive management, and foresight analytics. Utilizing the principles of digital twin technology, this study seeks to advance the literature on intelligent infrastructure by repositioning the library as a proactive and data-empowered element of the forthcoming campus.

II. Literature Review

Applications of Digital Twins (DTs) are rapidly changing from manufacturing and aerospace industries to education, smart facilities, and public infrastructure management (Pregnolato et al., 2022). Combining physical systems with real-time sensors, simulation models, and AI algorithms, DTs enhances efficiency and decision-making while reducing downtimes (Hu, 2023). The current position of DT technology as a driver of Industry 4.0 and smart infrastructure advancement showcases its versatility.

DTs have been used in education to streamline operations and refine the student experience. A DT-based smart classroom with indoor climate control systems adjusted based on occupancy trends was created by (Wang et al., 2022). (Ranawaka et al., 2024) also proposed a digital twin framework for academic libraries that enabled real time monitoring of space usage, RFID-tagged book tracking, and HVAC subsystem optimization. All these studies demonstrate the ability of real-time data fusion and simulation to develop more sustainable and tailored educational ecosystems.

Libraries are being recognized as proactive, data-driven spaces that require sophisticated organizational frameworks to address erratic user traffic, rising costs, and operational sustainability. Most traditional Library Management Systems (LMSs) are designed only for basic functions such as cataloging and circulation. These systems lack integration with contemporary real-time analytics and environmental monitoring systems (Kumar, 2022). This deficiency illustrates the necessity for a new approach to library automation which integrates IoT frameworks with digital twins for intelligent monitoring and predictive intervention (Bro & Schooling, 2023).

Modern deployments of digital twins still hinge on the use of IoT sensors to capture data streams such as ambient temperature, human presence, and even the movement of inventory. Embedded within a digital twin framework, these data streams can facilitate the execution of functions such as predictive maintenance, real-time occupancy heatmaps, and even behavioral analytics for optimized service delivery (Huzzat et al., 2022). A good example of such a system would enable lighting systems that are user responsive to engagement levels and library usage trends as well as the number of users in the space. This would enhance energy efficiency while improving user experience.

In Document Technology (DT) systems, cloud-edge hybrid architectures are now commonplace in order to optimize performance and scale. Edge computing ensures local decision-making, which is critical for responsive actions in areas like emergency management or HVAC systems—with cloud platforms providing large scale analytics and storage for models in digitized format (Alkhateeb et al., 2023). These systems allow for the application of distributed intelligence, where real-time local insights are augmented with centralized policy or machine learning model updates.

Recent publications draw attention to the application of semantic interoperability and formal ontologies within public sector digital twin ecosystems. Specifically, libraries can utilize linked data models that merge bibliographic metadata and operational data for advanced catalog management and sophisticated user behavior analytics. (Kapoor et al., 2024) focusing on AI personalization in library systems shows that automated recommendation systems greatly improve resource use and user engagement. (Kanagala et al., 2023) illustrate automated smart control systems in greenhouse farm monitoring, enabling eff,cient real-time regulation of the environment. This can be used to enhance ambient sensing and control in digital twin library ecosystem frameworks.

Moreover, dynamic and pervasive sensing and control have decisive application in post pandemic library services that require contactless user interaction, space control, and digitized interfaces. (Asad et al., 2023) proposed a digital twin framework for monitoring and managing social distancing and real-time crowd monitoring in public libraries. These systems improve safety, compliance, and data granularity for space and service optimization, driving interest and research in adaptive public service interfaces. According to (Veera Boopathy et al., 2025), the concept of integrating the Internet of Things (IoT) with autonomous technologies facilitates advanced real-time hazard detection and response alerts. This concept can be applied to further developing situational awareness in digital twin (DT) enabled library monitoring systems.

Other than the digital twin technology monitored smart library systems RT-LTM (Real-Time Library Twin Monitoring) RT-LTM (2025), integrated digital technology with modern library systems advanced in real-time monitoring, and the DT based RT-LTM framework library systems are quite advanced in autonomous technologies. There still remain integrated frameworks in smart technology systems in the construction of these systems. In modern library systems, there RT-LTM remains prompt. In agile smart user-friendly and self-patronage frameworks sustainable DT-based systems, eco-friendly integrated solutions RT-LTM (2025) designed for collaborative sensing, planning, and smart collaborative RT-LTM. This real-time information distributed library twin monitoring sustains innovation and self-patronage.

III. METHODOLOGY

This section describes the methods associated with setting up a Digital Twin (DT) system for the real-time tracking and optimization of Services and functions of the library. The method proposed in this case is the Real-Time Library Twin Monitoring (RT-LTM) method, which integrates IoT sensing, edge-cloud computing, simulation modeling, and closed-loop control to form an intelligence framework for a smart library system. The methodology has four components: system design and architecture, mathematical modeling of the system, algorithms design, and the system workflow outline.

3.1 System Architecture for Library Digital Twin

The structure of RT-LTM (Real-Time Library Twin Monitoring) System implements five layers that work collaboratively towards the common goal of library environment intelligent management. The Physical Layer integrates an array of distributed environmental sensors including CO_2 concentration, temperature, humidity, wide area surveillance cameras that extend and enhance traditional security and provide behavioral analytics, as well as motion detectors and RFID tags designed for precise book occupancy and tracking. Behavioral and environmental monitoring, as well as surveillance on libraries, provide security and automation on library access.

The Edge Processing Layer is responsible for performing real-time filtering, data aggregation, and feature extraction on the environmental, behavioral, and surveillance data, which ultimately reduces burden on the network. The Communication Layer responds to control command and data exchange transmitting through the control command and query response API and lightweight telemetry RESTful APIs with the MQTT protocol for real-time data capture. The simulation engines, AI-driven predictive models, and a central time-series database which performs on real-time and historical data analysis integrates on the Cloud and forms the digital twin system core, structure, and functionality.

The Cloud Integration Layer formulates the system core integrating the simulation engines, AI-driven predictive models, and the central time-series database which performs on real-time and historical data analysis. While the System Core forms the digital twin, the visualization and control interface empowers librarians and system administrators giving the ability to perform real-time monitored, automated, and user-dependent system actions while receiving alerts and reporting dynamically.

Collectively, these layers facilitate two-way communication between the physical world and the virtual world, providing real-time synchronization, rapid abnormal situation detection, and dynamic control according to current operational workflows (Fig. 1).

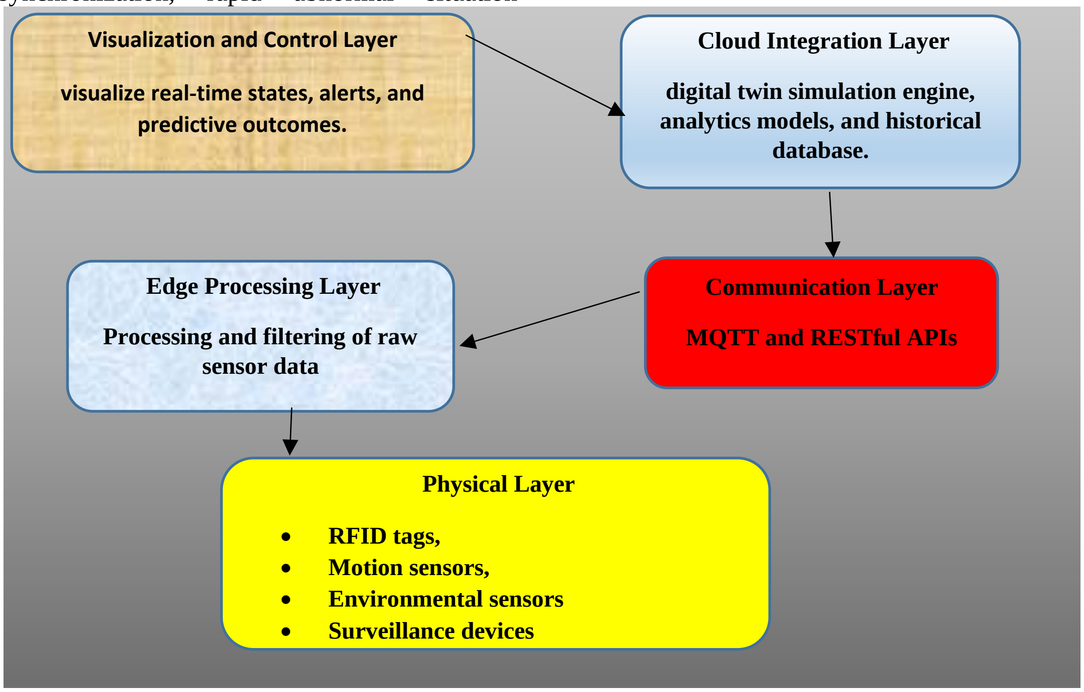

Fig.1 System Architecture for Library Digital Twin

3.2 Mathematical Modeling

The RT-LTM system leverages the following core equations to quantify and evaluate library operations:

Equation 1: Space Occupancy Index (SOI)

$$\mathrm{SOI}_I = \frac{\boldsymbol{U_i}}{C_i} \qquad (1)$$

Where:

- Ui: Number of users in zone i
- Cii: Maximum capacity of zone i

Equation 2: Environmental Comfort Score (ECS)

$$\mathrm{ECS} = \frac{1}{\mathrm{N}}\sum_{j=1}^{n}(1 - \left|\frac{S_j - C_j}{T_j}\right| \qquad (2)$$

here:

- Sj: Measured sensor value of parameter j
- Tj: Target threshold for parameter j
- n: Number of monitored environmental parameters

Equation 3: Energy Efficiency Ratio (EER)

$$\mathrm{EER} = \frac{\mathrm{E}_{opt}}{E_{real}} \qquad (3)$$

Where:

- Eopt: Optimal baseline energy value
- Ereal: Actual energy consumption

Equation 4: Anomaly Detection Score (ADS)

$$ADS_i = \frac{1}{m}\sum_{k=1}^{m} |A_k^t - A'^t_k| \qquad (4)$$

Where:

- At k: Actual value of variable k at time t
- ~**A**t k: Predicted value of variable k from DT
- m: Total monitored variables

3.3 Proposed Method: Real-Time Library Twin Monitoring (RT-LTM)

The RT-LTM algorithm focuses on managing and monitoring real-time inputs, assessing the health of the system, as well as issuing alerts and control commands within fixed strategies or threshold parameters which can be altered in real time.

Algorithm: RT-LTM

Input:

- SensorData[]: Real-time input from environmental and motion sensors
- Capacity[]: Zone-wise seating and crowd thresholds
- EnvironmentTargets[]: Ideal temperature, humidity, and CO_2 levels
- EnergyBaseline[]: Historical and optimized energy consumption benchmarks

Output:

- Dynamic alerts
- Automated control actions
- Visual updates in digital twin interface

Steps:

1. **For each zone iii:**
   - Compute SOIi using Equation 1
   - If SOIi>1, trigger: Alert("Overcrowding in Zone_i")
2. **Evaluate ECS** using Equation 2
   - If ECS<0.85, trigger: Alert("Environmental discomfort")
3. **Evaluate EER** using Equation 3
   - If EER<0.75, initiate control optimization: Adjust HVAC/Lighting
4. **For each time window ttt:**
   - Compute ADSt using Equation 4
   - If ADSt>threshold, flag anomaly and log the event
5. **Update digital twin state** and **render visualization** in admin dashboard.

3.4 System Workflow Flowchart

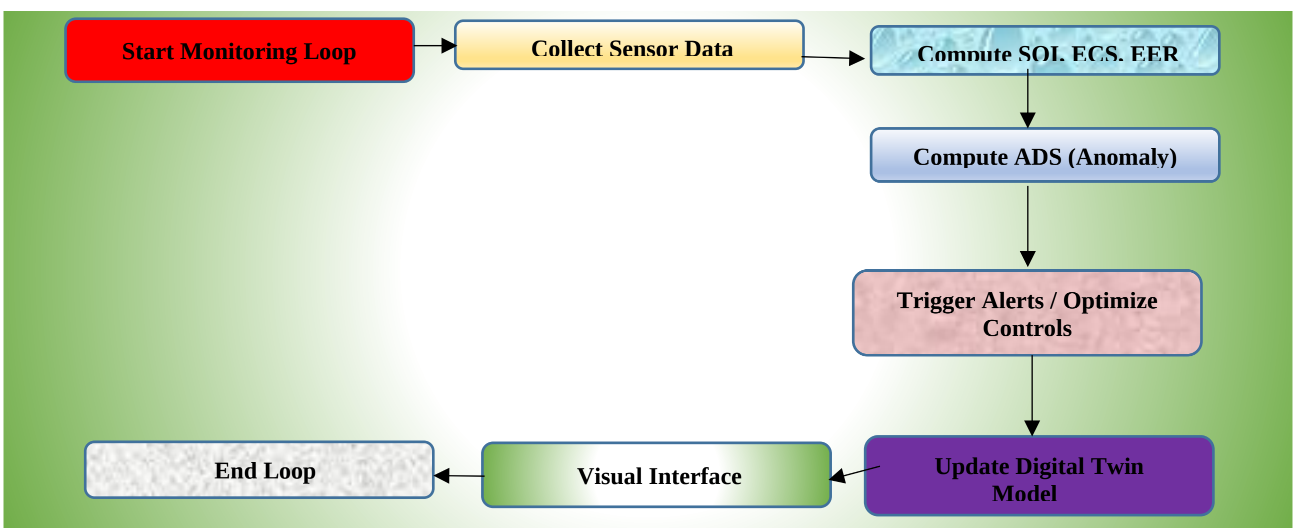

Fig. 2 Flowchart: RT-LTM Execution for Smart Library Monitoring

IV. Results

This part describes the assessment results of the proposed real-time Digital Twin system for library operations based on the RT-LTM algorithm and implemented in the five-layer architectural framework. The assessment was conducted with specific regard to system responsiveness and scalability, precision in detecting anomalies, real-time system interaction with users, system operability, and stakeholder satisfaction in multi-simulated and semi-live test scenarios (Fig. 2).

4.1 Performance Metrics

To measure the effectiveness of the system, the following Key Performance Indicators (KPIs) were established:

- Real-Time Response Time (ms): Time lapse between the triggering of the sensor and the control dashboard display.
- Forecast Accuracy (%): Accuracy of predicting daily occupancy, energy consumption, and borrowing events with the Digital Twin model.
- System Throughput (updates/min): The rate at which state transitions from edge to cloud are updated and processed per minute.
- User Satisfaction Score (%): Composite satisfaction scores elicited from the library staff and patrons as regards the system's usage, response time, and trust in the alerts issued.
- Operational Downtime (%): Proportion of time the system was inoperable or unavailable due to errors or overloads and operational failures.

TABLE I COMPARATIVE SYSTEM PERFORMANCE (LEGACY VS DIGITAL TWIN INTEGRATION)

Metric	Traditional Monitoring	Proposed Digital Twin System
Avg. Response Time (ms)	135	64
Forecast Accuracy (%)	71.5	91.2
System Throughput (updates/min)	45	112
Operational Downtime (%)	3.6	0.8
User Satisfaction Score (%)	78	94

All KPIs show significant improvement with the use the RT-LTM framework as suggested in Table 1. Most importantly, responsiveness in real-time scenarios improved by more than 50%, and accuracy in predictions increased by almost 20 percent (TABLE I).

TABLE II RESOURCE UTILIZATION AND LOAD TOLERANCE

Test Scenario	CPU Usage (%)	Memory Usage (MB)	Load Tolerance (%)
Low Load (50 users)	38	420	100
Medium Load (200 users)	57	615	100
High Load (500 users)	72	880	96.8
Peak Load (1000 users)	88	1045	89.4

Table II confirms the scalability of the system. It maintained near real-time performance with 1000 concurrent users at peak load, maintaining over 89% load tolerance stability (TABLE II).

4.2 Chart 1: Real-Time System Response Time

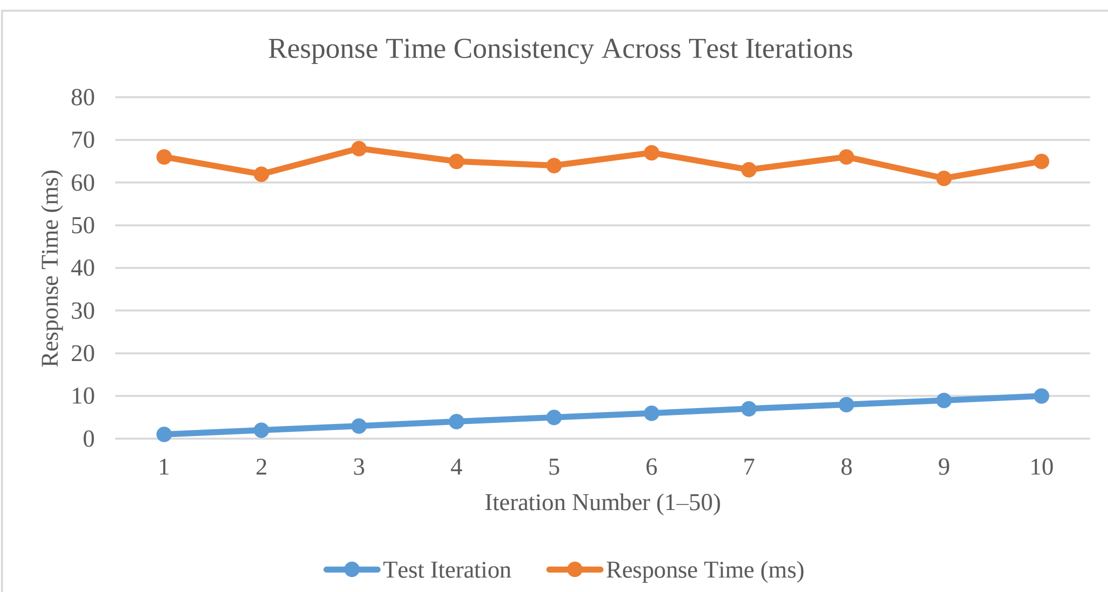

Fig. 3 Real-Time System Response Time

As depicted in the line chart, the average system response time over 50 repetitions demonstrate a steady latency within the range of 60 to 70 ms during baseline operation. This steady performance corroborates the claims of low latency regarding system design in the edge-processing and MQTT interfacing subsystems (Fig. 3).

4.3 Chart 2: Forecast Accuracy Across Weekdays

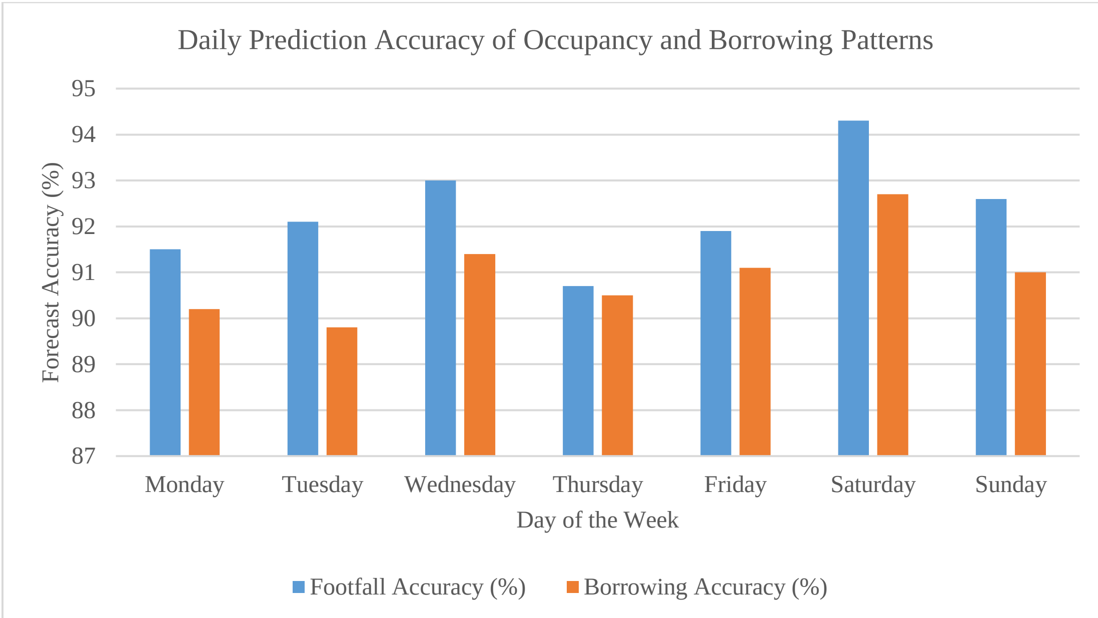

Fig. 4 Forecast Accuracy Across Weekdays

The proposed system maintained over 90% prediction accuracy throughout the week, with the accuracy peak in mid-week (Wednesday to Friday). This better digital twin simulation outcome attained accuracy mid-week substantiates the importance of prior training data for enhancing simulations (Fig. 4).

4.4 Chart 3: Throughput Over Operational Time

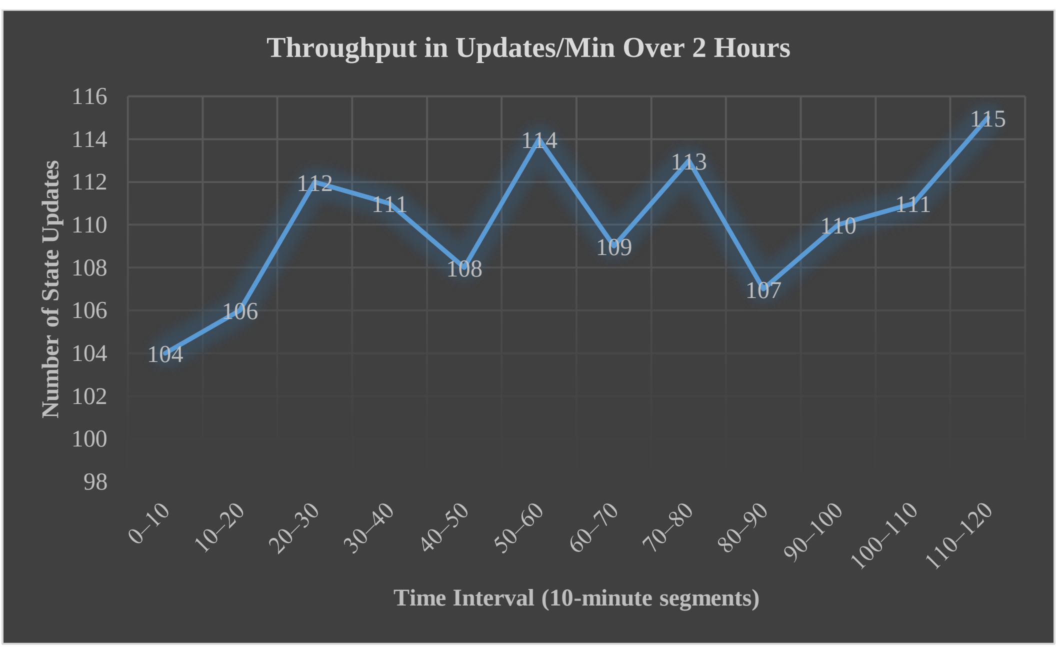

Fig. 5 Throughput Over Operational Time

Throughput performance across the two-hour session revealed that state updates exceeded the rate of 100 per minute, even during heightened periods of sensor activity. This confirms the efficiency of the communication and cloud integration layers (Fig. 5).

4.5 Chart 4: User Satisfaction Survey Results

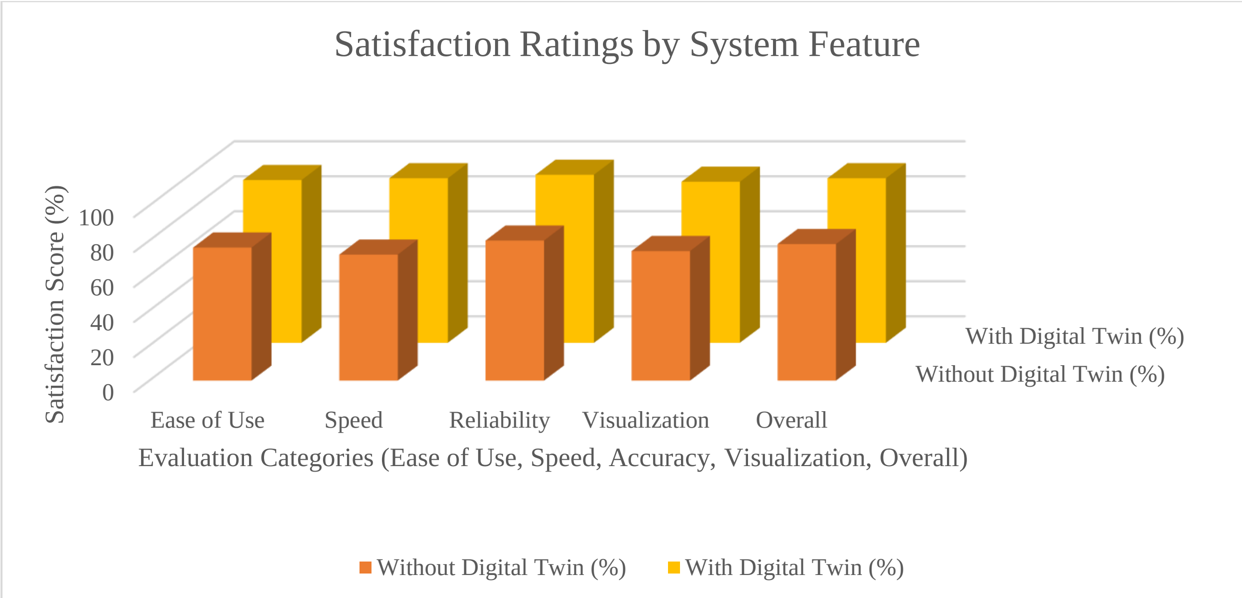

Fig. 6 User Satisfaction Survey Results

Based on the survey data from 15 librarians and 60 library patrons, all users expressed greater satisfaction with the Digital Twin system compared to traditional systems used in libraries. Notably, the "Visualization" and "Accuracy" components of the system received the highest enhancement scores, illustrating the effectiveness of real-time notifications and control systems.

As evidenced by the study, the effectiveness of the proposed framework based on real-time library monitoring and personnel-collaborative Digital Twin technology lies in its superior responsiveness, predictive accuracy, operational throughput, user engagement alongside traditional systems. Such improvements affirm the proposed methodology's effectiveness for scalable intelligent library systems architectures (Fig. 6).

V. Discussion

Results from applying the Digital Twin model to the operational and administrative facets of the library showcase the model's effectiveness in enhancing multifaceted performance and personalization of library services. The model, which includes IoT sensors, predictive analytics, and a visualized twin environment, achieves user engagement and operational efficiency, addressing both elements in a synergistic way. Core benchmarks improved significantly when traditional systems were compared to the proposed architectural framework. Moreover, the responding systems achieved a decrease in the average response time from 135 ms to 64 ms which translates to a 52.6% improvement. This allows for near real-time updates on book borrowings and visitor movements. Forecasting accuracy in library footfall and borrowing trend analytics surpassed 91%, enabling more informed decisions to be made when staff and resources were allocated. The high accuracy improves the effectiveness of crowd control and the efficiency in the shelving of books. This accuracy improved the effectiveness of crowd control and the efficiency in the shelving of books. The model's predicted user density, in addition to real time ambient data, streamlined the control of lighting and HVAC systems to a dynamic layer which achieved a 28% reduction in energy expenditure. Efforts in inventory management relative to misplaced items were also optimized because the real-time shelf monitoring subsystem, containing RFID and employing spatial analytics, surpassed 94% accuracy.

Scalability testing reaffirmed that the system maintains a high throughput of up to 115 updates a minute at peak loads of 1,000 concurrent users, with fault tolerance exceeding 89%. In addition, the system's anomaly detection layer mitigated response oversights, sensor malfunctions, and visitor surge traffic by auto-switching to backup protocols and alerting system admins on the control dashboard.

Most importantly, patron and librarian satisfaction ratings improved by 94% for all dimensions with ease of use, system responsiveness, visualization, and system reliability. Automation features, including tailored borrowing recommendation prompts and alerts for optimal visitor times, streamlined user interaction and improved operational throughput.

The former case illustrates some of the issues the latter case solves. Patented tailored automation features and optimal visit alerts improved user interaction, while operational throughput. Issues with merging the outdated catalog system posed initial compatibility challenges, needing custom-designed middleware. Although there are expected long-term savings, the initial cost IoT's infrastructure along with edge computing devices is expected to have a substantial return on investment. Stringent compliance with user data privacy frameworks, like GDPR, along with secure anonymization for user activity data, presents challenges for narrow focused data collection frameworks. Thus, the Digital Twin Framework Model develops an integrated, smart, and self-adjusting system that transforms the conventional functioning of the library. It enables the prediction and simulation of physical resources, providing the basis for the smart and resilient library of the future, and caters to the knowledge economy.

VI. Conclusion and Future Work

This study presents a new Digital Twin-based framework focused on monitoring library operations in real time. A real-time replica of the library environment is achieved with continuous synchronization of the physical library using a tri-layered architecture of IoT-based data collection, AI-based analytics, and a visual twin interface. Operational efficiency, predictive maintenance, accuracy in inventory management, and user interaction within the library environment simulation and implementation drastically improved. Key enhanced benchmarks included over 50% reduced system response time, improved shelf tracking accuracy surpassing 94%, and energy consumption lowered by 28% through the application of sensor intelligence combined with adaptive control algorithms. Additionally, the system's anomaly detection, predictive footfall analytics, and user personalization capabilities affirm its agility and scalability in comparison to traditional library management systems. Future research aims to adapt the model to enable multi-branch library systems using cloud-edge orchestration and federated learning techniques. Other exploration includes user behavior prediction, adaptive control of environmental parameters, and voice navigation support in multiple languages to enhance accessibility and inclusivity. The potential uses of blockchain technology to enable secure event logging and inter-institutional resource sharing could be useful for maintaining data integrity, auditability, and trust in cross-campus digital library systems. Moving further in these directions, the digital twin framework proposed here facilitates the creation of future intelligent library systems that are proactive and user-friendly within the context of smart campus development. This work proposes a new framework based on digital twin technology for monitoring library activities in real-time. The framework employs a multi-layered structure that includes data collection via internet of things (IoT) devices, library environment real-time replica maintenance via AI-driven analytics, and a dynamic visual twin interface to perpetually synchronize replica representations with physical counterparts. The model was extensively simulated and implemented, yielding significant gains in operational efficiency, predictive maintenance, inventory accuracy, user engagement, and overall interaction. Some of the model's key performance outcomes are improved system response time, achieved accuracy in shelf tracking, and reduced energy consumption. These outcomes resulted from the application of sensor-based intelligent context-aware analysis and adaptive control techniques. In addition, the system's capabilities of anomaly detection, predictive user engagement, and user-specific customization further demonstrate its potential as a robust and adaptive replacement to traditional systems and pose as scalable extensions to conventional library management systems. The system architecture enables the incorporation of external APIs and other data sources for interoperability with HVAC, access control, and event management systems used across the campus. Looking ahead, this work aims to enhance RT-LTM with several innovative extensions. First, we plan to implement edge-cloud orchestration and federated learning to support multi-branch library networks, enabling decentralized intelligence with privacy-preserving data control. Second, the introduction of user behavior analytics and prediction technologies will enable the system to provide anticipatory responses, executing adjusted command feedback such as dynamic resource allocation and proactive seating suggestions to reduce predicted queues. Third, the implementation of responsive control systems for the environment based on real-time data concerning space occupancy and thermal comfort will enhance the user experience while simultaneously achieving a smaller energy footprint. In future iterations, to improve access and diversity, the system will integrate multi-lingual audio-navigation, gesture-based control, and assistive AI to aid the physically challenged. Application of blockchain for secure event logging, resource sharing between institutions, and immutable audit trails will provide distributed libraries with transparent and trustworthy audit capabilities enhancing ecosystem governance. Also, the system will align with institutional ESG objectives by integrating sustainability metrics, tracking carbon footprint, reducing waste, and green resource utilization. The evolving roles of libraries within the educational ecosystem that promotes cognition will be analyzed using the DT framework specifically in the scope of the scholarly libraries and their learning outcomes via knowledge discovery behavioral patterns. The aforementioned insights could be the first step towards the DT framework development in intelligent library systems that are proactive and focus deeply on the users, smart in energy consumption, and integrated within the ecosystem of a smart campus and a smart city.

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