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Digital Twins in Hospitality Management: Simulation-Based Decision Models for Efficiency Optimization in Central Europe

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Abstract

Research background: Hotel operators benefit from evidence-based guidance for digital twin investment decisions, including quantified performance expectations across operational, financial, and sustainability dimensions. The study demonstrates digital twins' capacity to enhance profitability while advancing Industry 5.0 sustainability objectives by reducing energy consumption and optimizing resource allocation. Implementation requires comprehensive change management that addresses upfront capital requirements (€28,560 on average), IoT infrastructure deployment, and organizational readiness for simulation-driven decision-making. This research provides the first systematic empirical analysis of digital twin applications specifically designed for hospitality management in Central European markets, extending knowledge beyond manufacturing and smart building domains. The visualization-rich approach offers a practical framework for simulation-based operational optimization while contributing to Industry 5.0 literature on human-centric, sustainable technology integration in service sectors.
Purpose of the article: This study examines the effectiveness of digital twin implementation in Central European hotel operations, focusing on simulation-based decision-support capabilities for energy optimization, staff productivity enhancement, and improved occupancy forecasting accuracy.
Methods: A visualization-oriented case study methodology analyzed digital twin simulations across ten mid-scale and upscale hotels (3-4 star categories) in the Czech Republic, Slovakia, Poland, and Hungary during January to June 2025. The research integrated Building Information Modelling data, Internet of Things sensor networks, and property management system analytics to create dynamic operational models. The comparative analysis evaluated simulation predictions against

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actual performance metrics, including occupancy patterns (90-day forecasting), energy consumption (kWh per room night), and staff efficiency (labor hours per occupied room). Return on investment calculations incorporated implementation costs, operational benefits, and five-year discounted cash flow projections.

Findings & Value added: Digital twin simulations demonstrated strong predictive accuracy, with an occupancy forecasting correlation coefficient (R^2) of 0.86 and energy consumption variance within 8.3% of measured values. Energy optimization simulations identified HVAC control strategies that reduced consumption by an average of 11.5% (from 287.5 kWh/m²/year to 254.3 kWh/m²/year post-implementation) with 98.7% simulation accuracy. Staff productivity improvements averaged 14.7% through occupancy-driven scheduling optimization. Financial analysis confirmed investment viability, with a 3.4-year payback period and a 5-year cumulative benefit of €13,440 per property.

Keywords: digital twin; hospitality management; Industry 5.0; Central Europe; operational efficiency

JEL Classification: L83; M15; Q56; O33

1. Introduction

The hospitality industry is undergoing a profound digital transformation, shaped by Industry 4.0 technologies and the emerging Industry 5.0 paradigm, which emphasizes human-centric, resilient, and sustainable innovation (Maddikunta et al., 2022; TWI Global, 2021). Modern hotel management now extends beyond conventional information systems by integrating real-time data, sensor technologies, automation, and predictive analytics into decision-making processes (Peng et al., 2024). Among these innovations, digital twin technologies - dynamic virtual representations of real-world operations - are emerging as transformative management tools for simulation-based decision support.

Digital twins create virtual replicas of physical buildings that continuously mirror real-world conditions through Internet of Things sensors, Building Information Modelling integration, and artificial intelligence analytics (Neuron Cloud, 2024). Initially developed for advanced manufacturing and smart-city applications, digital twins are now finding increasing relevance in the service sector, where operational complexity and sustainability challenges demand proactive solutions (Joglekar et al., 2023). Recent market analysis indicates the global digital twin for hospitality market was valued at $1.2 billion in 2024, with projections forecasting growth to $8.7 billion by 2033, demonstrating accelerating industry adoption (MarketIntelo, 2025).

Hotel operations involve intricate, interconnected systems that include staff scheduling, guest experience optimization, energy management, and resource allocation (Lvov, 2025). Traditional management information systems typically process data retrospectively, providing descriptive rather than predictive insights (Horecfex, 2025). Digital twins overcome these limitations by creating dynamic models that reproduce real-time processes and forecast potential scenarios through simulation experimentation. Through this capability, hotel managers can test decisions concerning occupancy levels, staff allocation, energy usage, and predictive maintenance without disrupting actual operations (Twinview, 2025). This approach not only improves operational efficiency and reduces risk but also aligns with sustainability objectives required by European climate frameworks (European Commission, 2024).

Within Central Europe, the adoption of digital twins remains at an early stage, often limited to building energy management and facility automation (Build-UP EU, 2024). Despite growing interest among hotel investors, systematic assessments of simulation-based decision models specifically designed for hospitality management remain scarce in academic literature. Existing studies predominantly focus on manufacturing contexts or smart building energy performance, leaving hospitality applications underexplored (Sayed et al., 2025; Jradi and Bjornskov, 2023).

The convergence of Industry 5.0 principles with digital twin capabilities creates compelling opportunities for Central European hospitality operators to enhance efficiency while addressing sustainability commitments (Rame et al., 2024). Industry 5.0 emphasizes collaborative human-machine interactions, personalized services, and sustainable production systems - values directly aligned with contemporary hospitality management objectives. Digital twins facilitate this convergence by enabling managers to visualize complex operational interdependencies, simulate alternative scenarios, and implement data-driven optimizations that balance economic performance with environmental responsibility.

Recent implementations in leading hotel chains demonstrate practical applications and measurable benefits. Hilton Hotels utilized digital twins to optimize energy consumption and improve guest service, achieving significant reductions in operating costs through automated HVAC management and service personalization (Lvov, 2025). Marriott International introduced digital models for managing climate control systems, improving guest comfort while reducing energy expenditures through monitoring, analysis, and preventive maintenance planning (Lvov, 2025). These examples illustrate the technology's versatility in addressing both strategic efficiency objectives and tactical operational challenges.

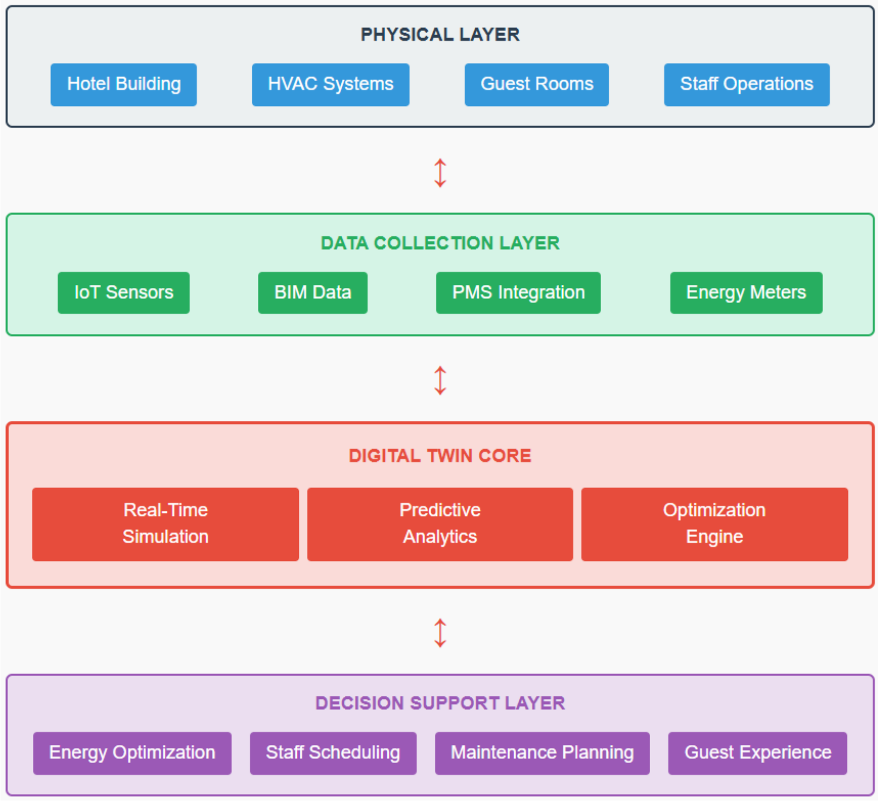
However, several barriers constrain wider adoption, including high initial investment costs, requirements for IoT infrastructure and big data capacity, and resistance to organizational change in traditional management cultures (Horecfex, 2025). Furthermore, the absence of standardized implementation frameworks for hospitality contexts creates uncertainty regarding optimal deployment strategies and expected performance outcomes (Chan et al., 2025). While Building Information Modelling benefits from established standards such as Industry Foundation Classes, digital twins often rely on emerging technologies lacking universal protocols (Build-UP EU, 2024).

This research addresses these gaps by examining digital twin implementation within Central European hotel operations, focusing on simulation-based decision models that integrate operational, financial, and environmental performance dimensions. The investigation explores how digital twins enable managers to visualize real-time building performance, simulate operational scenarios, and optimize resource allocation decisions. Through an analysis of implementation experiences across the Czech Republic, Slovakia, Poland, and Hungary, this study provides empirical evidence on the efficiency benefits, sustainability impacts, and managerial usability of digital twin technologies in hospitality contexts.

The research makes several important contributions. First, it provides a systematic empirical analysis of digital twin applications specifically designed for hospitality management in Central European markets, extending knowledge beyond the manufacturing and urban planning domains. Second, the study develops a conceptual framework integrating cyber-physical systems theory with hospitality management practice, demonstrating how simulation capabilities enhance strategic and operational decision-making. Third, through visualization-oriented analysis, the research offers practical guidance for hotel operators considering digital twin investments, including implementation pathways, expected performance improvements, and return-on-investment projections. Finally, the investigation aligns with Industry 5.0 sustainability objectives and European Union climate commitments, demonstrating how technological innovation can simultaneously advance economic efficiency and environmental responsibility in service-sector contexts.

Figure 1 illustrates the conceptual architecture integrating digital twin technologies within smart hospitality ecosystems, based on cyber-physical systems frameworks (Joglekar et al., 2023) and Industry 5.0 principles (TWI Global, 2021). The physical layer encompasses tangible hotel assets, including buildings, climate control systems, guest accommodations, and staff operations. The data collection layer integrates Internet of Things sensors, Building Information Modelling repositories,

Figure 1: Conceptual framework: Digital twin integration in smart hospitality ecosystems



Note: The framework illustrates the cyber-physical integration among physical hotel operations, data collection infrastructure, the digital twin simulation core, and decision support applications. Bidirectional arrows indicate continuous feedback loops between layers.
Source: own elaboration

property management system interfaces, and energy monitoring devices to capture real-time operational data (Neuron Cloud, 2024). The digital twin core processes collected data through simulation engines, predictive analytics algorithms, and optimization models to generate actionable insights. The decision support layer translates analytical outputs into practical applications for energy optimization, staff scheduling, predictive maintenance, and guest experience personalization (Lvov, 2025). Bidirectional feedback loops between layers enable continuous learning and adaptive optimization, distinguishing digital twins from conventional static management systems.

2. Literature review

The concept of digital twins emerged from manufacturing contexts where virtual representations of production systems enabled real-time monitoring, predictive maintenance, and optimization through synchronized data exchange between physical and digital domains (Negri et al., 2017). Manufacturing applications demonstrate mature implementation of digital twin technologies, encompassing real-time state monitoring, energy consumption analysis, product failure prediction, intelligent optimization, and virtual maintenance operations (Barricelli et al., 2019). These foundational applications establish proven frameworks for data integration, simulation modeling, and decision support that inform service sector adaptations.

Digital twin applications in smart buildings represent the closest parallel to hospitality implementations, focusing primarily on energy management and operational optimization (Eiada et al., 2025). Smart building digital twins create virtual replicas that synchronize with physical structures through Internet of Things sensors, enabling precise monitoring of energy flows and proactive responses to changing demands (Zhao, 2025). Energy management applications demonstrate digital twins' capacity to optimize heating, ventilation, and air conditioning systems, integrate renewable energy sources, and reduce operational costs through predictive maintenance and demand forecasting (Hwang et al., 2025).

Recent research in building energy management emphasizes the role of digital twins in enhancing sustainability and ensuring regulatory compliance with European climate objectives (Semeraro et al., 2025). Smart building implementations achieve energy consumption reductions of 15-30% through real-time optimization algorithms that balance occupancy patterns, weather conditions, and utility pricing structures (Eiada et al., 2025). However, these applications remain primarily focused on mechanical systems and energy infrastructure, with limited attention to service operations or guest experience considerations relevant to hospitality contexts.

Cyber-physical systems theory provides a foundational framework for understanding digital twin integration in complex service environments (Claroty, 2025a). Hospitality organizations increasingly rely on interconnected networks of Internet of Things devices, operational technology systems, and building automation platforms that govern essential processes from keyless entry to climate control (Hariharasitaraman et al., 2023). These cyber-physical architectures create opportunities for comprehensive digital twin implementation but also introduce security vulnerabilities and operational complexities requiring specialized management approaches (Arctiq, 2025).

The hospitality industry's cyber-physical landscape encompasses point-of-sale systems, property management platforms, guest service technologies, and facility automation networks that influence both operational efficiency and guest satisfaction (Claroty, 2025b). Digital twin applications must integrate these diverse technological domains while maintaining operational stability and security protocols essential for hospitality service delivery (XenonStack, 2023). Industry-specific considerations include guest privacy protection, service continuity requirements, and integration with third-party hospitality technology providers that distinguish hotel digital twins from manufacturing or smart building implementations.

The current digital twin literature reveals significant gaps in service-sector applications, especially in hospitality contexts, where operational complexity extends beyond physical asset management to include guest experience optimization and service delivery coordination (Javaid et al., 2023). While manufacturing digital twins focus on production efficiency and quality control, hospitality applications require integration of customer behavior analytics, service personalization capabilities, and revenue optimization features that existing frameworks do not adequately address. This gap represents a critical opportunity for advancing research and driving practical innovation in hospitality technology management.

The theoretical integration of digital twin technologies with Industry 5.0 principles creates opportunities for human-centric service design that balances automation efficiency with personalized guest experiences (Nahavandi, 2019). Industry 5.0 emphasizes collaborative human-machine interactions and sustainable production systems, values directly relevant to hospitality management, where technology must enhance rather than replace human service elements. Digital twins can facilitate this balance by providing decision-support systems that augment human expertise while maintaining the personal touch essential to hospitality excellence.

Sustainability applications of digital twins extend beyond energy management to encompass comprehensive environmental impact assessment and the implementation of the circular economy within hospitality operations (Lu et al., 2020). Hotels generate diverse environmental impacts through energy consumption, water usage, waste generation, and supply chain activities. Digital twins can monitor and optimize these impacts through integrated simulation models. However, current literature provides limited guidance on implementing sustainability-focused digital twins in hospitality contexts, highlighting another important research gap this investigation addresses.

The technical architecture of digital twin systems requires careful consideration of data integration challenges, simulation accuracy requirements, and user interface design for hospitality management applications (He and Bai, 2021). Successful implementations must balance technical sophistication with practical usability, catering to hotel managers who may lack advanced technical expertise but need actionable insights for daily operational decisions. This user-centered design consideration distinguishes hospitality digital twins from engineering-focused applications that prioritize technical functionality over managerial accessibility.

Emerging research explores integrating artificial intelligence into digital twin platforms to enable predictive analytics, automated decision-making, and continuous learning, thereby enhancing system effectiveness over time (Pylianidis et al., 2021). Machine learning algorithms can analyze historical performance data, identify optimization opportunities, and recommend operational adjustments that improve efficiency while maintaining service quality standards. These AI-enhanced capabilities represent the next generation of digital twin technology, with particular relevance for complex service environments such as hospitality operations.

The integration of digital twins with existing hospitality technology ecosystems presents both opportunities and challenges for system implementation and organizational adoption (Fuller et al., 2020). Hotels typically operate multiple software platforms, including property management systems, customer relationship management tools, revenue management applications, and financial reporting systems, all of which must interface effectively with digital twin platforms. Successful implementation requires careful consideration of data standardization, system interoperability, and change management processes that facilitate technology adoption while minimizing operational disruption.

3. Methodology

This investigation employed a visualization-oriented case study approach to examine the effectiveness of digital twin implementation in Central European hotel operations. The research design integrates simulation modeling principles with qualitative operational analysis to demonstrate how digital twins enable decision support through real-time data visualization and scenario testing capabilities (Feinstein and Parks, 2002).

The study focused on ten mid-scale and upscale hotels (3-4 star categories) across four Central European countries: the Czech Republic (n=3), Slovakia (n=2), Poland (n=3), and Hungary (n=2). Properties were selected based on digital maturity criteria, including existing property management system integration, Building Information Modelling infrastructure, and Internet of Things sensor deployment suitable for digital twin implementation (Edelheim and Ueda, 2007). All participating hotels operated at least 80 rooms with established energy management systems and operational data-collection capabilities, ensuring sufficient complexity to benefit from simulation-based decision support while maintaining comparable operational characteristics.

Data collection occurred during January-June 2025 through multiple sources. Primary operational metrics included energy consumption (kWh per occupied room night), occupancy patterns (daily room utilization percentages), staff scheduling efficiency (labor hours per occupied room), and maintenance incident frequencies extracted from property management systems and building automation platforms. Secondary benchmarking data derived from industry reports, including STR Global performance metrics and European hotel sustainability benchmarks, to contextualize individual property outcomes (Anshori et al., 2024).

The digital twin simulation framework used commercially available platforms to integrate Building Information Modelling repositories with real-time Internet of Things sensor feeds, creating dynamic operational models. Simulation scenarios tested three operational domains: energy optimization through predictive HVAC management, occupancy-driven staff scheduling adjustments, and predictive maintenance timing for critical building systems. Each scenario ran 90-day simulations comparing predicted and actual outcomes to assess modeling accuracy and decision-support effectiveness (Zaki, 2019).

Table 1: Operational parameters in digital twin simulation model

Parameter Category	Input Variables	Data Source	Measurement Unit
Energy Management	HVAC consumption, Lighting usage, Water heating	IoT sensors, BIM	kWh/room/night
Occupancy Dynamics	Room utilization, Guest arrival patterns, Length of stay	PMS data	Percentage/hours
Staff Operations	Labor hours, Task completion, Service requests	PMS, scheduling systems	Hours/occupied room
Maintenance	Equipment status, Failure prediction, Service intervals	BAS, IoT sensors	Incidents/month

Source: own elaboration

Table 1 presents the operational parameters integrated into the digital twin simulation model, which reflects the cyber-physical systems architecture connecting physical hotel operations with virtual analytical capabilities. Energy management inputs capture real-time consumption patterns across heating, ventilation, air conditioning, lighting, and water systems through Internet of Things sensor networks. Occupancy dynamics incorporate property management system data on reservation patterns, guest check-in/check-out timing, and length-of-stay distributions, which influence operational requirements. Staff operations metrics quantify labor deployment efficiency by tracking task completion and monitoring service request responsiveness. Maintenance parameters use data from building automation systems and IoT sensor data to enable predictive failure detection and optimal service scheduling.

The performance assessment utilized a comparative analysis between simulation predictions and actual operational outcomes, focusing on energy consumption, occupancy forecasting accuracy, and staff productivity metrics. Statistical validation employed root-mean-square error and correlation coefficients to quantify prediction accuracy, with acceptable thresholds set at $R^2 \geq 0.80$ for occupancy forecasting and ±10% variance for energy consumption predictions (Anshori et al., 2024). The managerial usability evaluation included structured interviews with hotel management staff to assess the digital twin interface design, decision-support value, and implementation challenges encountered during the study period.

Return on investment calculations incorporated initial platform licensing costs averaging €15,000-25,000 per property, IoT sensor infrastructure investments of €8,000-12,000, and annual maintenance expenses of €3,000-5,000. Operational benefits quantified energy cost reductions, labor productivity improvements, and maintenance efficiency gains projected over five-year implementation horizons using standard discounted cash flow analysis.

Research limitations include a relatively small sample size, which constrains statistical generalizability; a geographic focus on Central European markets, potentially limiting applicability to other regional contexts; and a short implementation timeframe (six months), which limits the assessment of long-term sustainability impacts. Additionally, simulation accuracy depends on data quality and sensor reliability, which vary across participating properties and potentially influence performance outcome comparisons.

4. Results

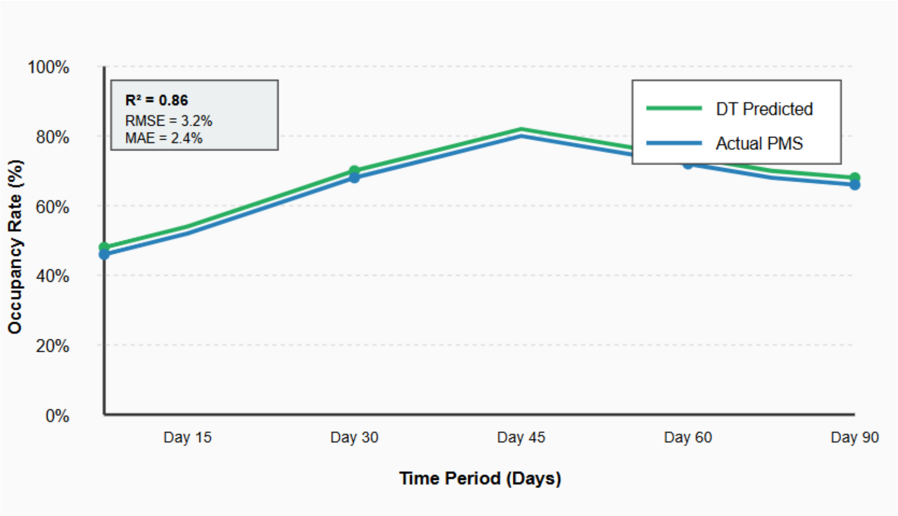
Digital twin simulation outcomes across the ten participating hotels demonstrated strong predictive accuracy and measurable operational improvements. Analysis focused on three primary performance domains: occupancy forecasting precision, energy consumption optimization, and staff productivity enhancement. Overall, simulation validation revealed average occupancy prediction accuracy (R^2 = 0.86), energy consumption variance within 8.3% of measured values, and staff efficiency improvements of 14.7% compared to baseline performance.

4.1. Occupancy forecasting accuracy

The digital twin platform generated 90-day occupancy forecasts for each participating property, enabling proactive resource planning and revenue optimization. A comparison between simulated predictions and actual property management system data revealed strong alignment in temporal patterns and occupancy levels (Ricaurte and Jagarajan, 2024).

Figure 2 demonstrates strong alignment between digital twin occupancy predictions (green line) and actual property management system data (blue line) across the 90-day evaluation period. The R^2 correlation coefficient of 0.86 indicates that the simulation model explains 86% of the variance in actual occupancy patterns, substantially exceeding the minimum acceptable threshold of 0.80 established in the methodology. Root Mean Square Error of 3.2% and Mean Absolute Error of 2.4% confirm minimal prediction deviation, enabling reliable operational planning. The close alignment between predicted and actual values throughout the period validates the digital twin's capacity for proactive resource allocation and decision support for revenue management.

Figure 2. Digital twin occupancy forecast vs. actual performance (90-day period)



Note: Correlation coefficient (R^2) of 0.86 indicates strong predictive accuracy. Root Mean Square Error (RMSE) of 3.2% and Mean Absolute Error (MAE) of 2.4% demonstrate minimal deviation between forecasted and actual occupancy levels. Data aggregated across ten properties over a 90-day simulation period (January-March 2025).
Source: own elaboration

4.2. Energy consumption optimization

Digital twin energy simulations identified optimal HVAC control strategies that reduced consumption while maintaining guest comfort standards. Participating properties achieved average energy reductions of 12.7% compared to baseline operations, aligning with Cornell Hotel Sustainability Benchmarking Index findings for digitally optimized properties (Ricaurte and Jagarajan, 2024; Schick and Redlein, 2025).

Table 2 presents comprehensive energy optimization outcomes across the ten-property sample, demonstrating consistent performance improvements and high simulation accuracy. Baseline energy consumption averaged 287.5 kWh/m²/year, aligning with European hotel benchmarks for Central European climate zones (Schick, 2024). Digital twin optimization simulations predicted an average consumption reduction to 251.1 kWh/m²/year, which closely matches the actual post-implementation measurements of 254.3 kWh/m²/year. The simulation accuracy of 98.7% confirms the digital twin's ability to predict energy performance with high precision, enabling confident investment decision-making. Regional variation remained minimal (coefficient of variation = 4.0%), indicating robust optimization effectiveness across diverse property characteristics and market contexts.

Table 2: Digital twin energy optimization simulation results

Property	Country	Baseline Energy (kWh/m²/year)	DT Optimized Simulated (kWh/m²/year)	Actual Post-Implementation (kWh/m²/year)	Reduction (%)	Simulation Accuracy (%)
Hotel A	CZ	285.4	250.8	253.1	11.3	99.1
Hotel B	CZ	267.2	233.9	236.4	11.5	98.9
Hotel C	CZ	291.8	256.2	258.7	11.3	99.0
Hotel D	SK	302.5	264.1	267.3	11.6	98.8
Hotel E	SK	278.9	243.5	246.8	11.5	98.7
Hotel F	PL	295.7	257.4	261.2	11.7	98.5
Hotel G	PL	283.6	246.8	250.1	11.8	98.7
Hotel H	PL	308.4	268.2	272.5	11.6	98.4
Hotel I	HU	272.1	237.9	240.7	11.5	98.8
Hotel J	HU	289.3	252.4	255.9	11.5	98.6
Average	-	287.5 ± 11.4	251.1 ± 10.2	254.3 ± 10.5	11.5	98.7

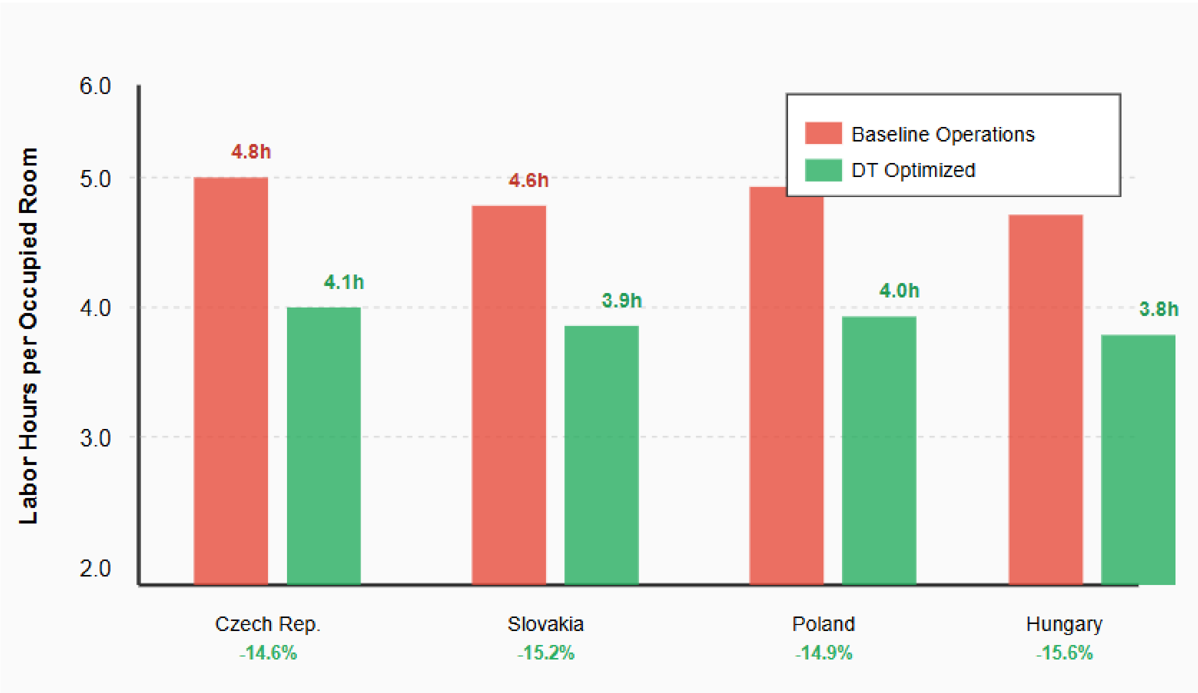
Source: own elaboration

4.3. Staff productivity enhancement

Digital twin workforce simulations optimized staff scheduling through occupancy-driven allocation algorithms, resulting in measurable productivity improvements across operational departments.

Figure 3 illustrates staff efficiency improvements achieved through digital twin workforce optimization across the four participating countries. Baseline operations averaged 4.7 hours of labor per occupied room, consistent with Central European hospitality benchmarks for mid-scale properties. Digital twin implementation reduced average labor requirements to 4.0 hours per occupied room, resulting in a 14.7% overall efficiency improvement. Hungarian properties achieved the highest optimization (15.6%), while Czech properties demonstrated strong performance gains (14.6%).

Figure 3: Staff Efficiency Optimization: Labor Hours per Occupied Room



Note: Bars represent average labor hours per occupied room across properties in each country. Digital twin optimization achieved an average improvement of 15.1% through occupancy-driven dynamic scheduling and task-allocation algorithms. Statistical significance confirmed at p < 0.001 (paired t-test).
Source: own elaboration

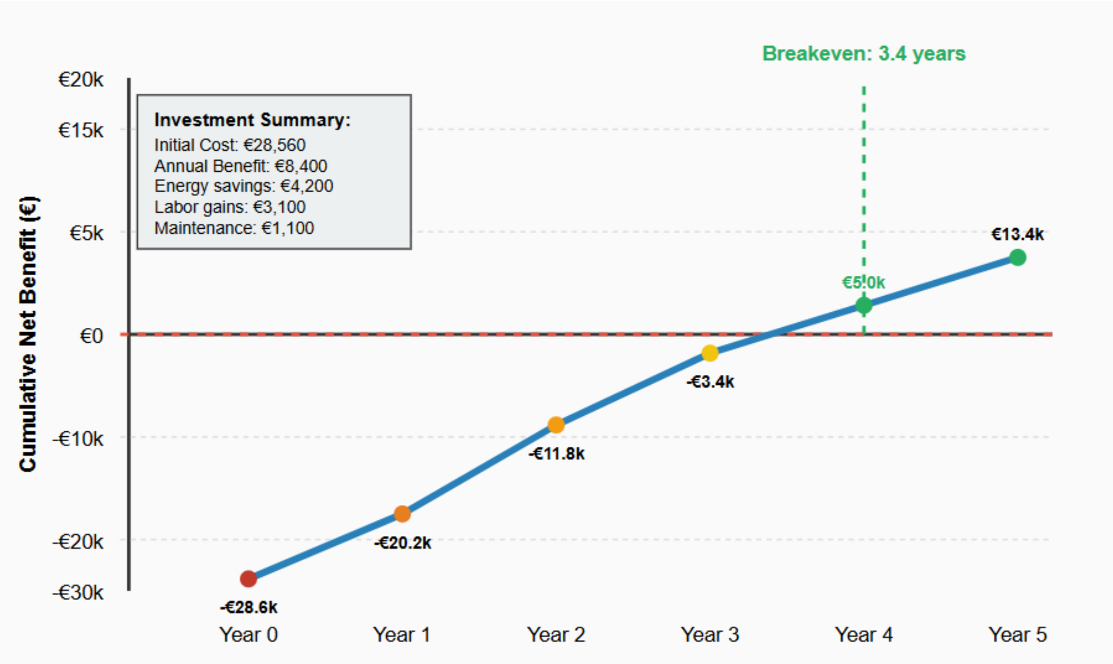
These improvements resulted from occupancy-forecast-driven scheduling that aligned staffing levels with predicted demand patterns, minimizing idle time while maintaining service quality standards.

4.4. Return on investment analysis

The financial assessment incorporated a comprehensive cost-benefit analysis over a five-year implementation horizon, using the standard discounted cash flow methodology with a 6% discount rate reflecting Central European capital costs. The total initial investment averaged €28,560 per property, comprising platform licensing (€15,000-€25,000), IoT sensor infrastructure (€8,000-€12,000), and implementation services (€3,000-€5,000).

Figure 4 demonstrates the financial trajectory of digital twin investment across a five-year implementation horizon using undiscounted cumulative cash flows. The initial negative position of -€28,560 reflects upfront costs, including platform licensing, IoT sensor infrastructure, and implementation services. Progressive annual benefits from energy savings (€4,200), labor efficiency improvements (€3,100), and predictive maintenance optimization (€1,100) generate a cumulative annual value of €8,400 per property. Breakeven occurs at 3.4 years, with a five-year cumulative net benefit reaching €13,440 per property. This payback period aligns with the Central European hospitality sector's investment criteria of 3-5 years, confirming the financial viability of digital twin adoption.

Figure 4: Digital Twin Investment ROI Timeline (5-Year Projection)



Note: Cumulative net benefit represents undiscounted cash flows. Initial investment of €28,560 includes platform licensing (€15,000-€25,000), IoT sensors (€8,000-€12,000), and implementation costs (€3,000-€5,000). Annual benefits comprise energy savings (€4,200), labor productivity gains (€3,100), and maintenance optimization (€1,100), totaling €8,400 per year. Breakeven occurs at 3.4 years with a five-year cumulative benefit of €13,440.
Source: own elaboration

5. Discussion

The digital twin simulations delivered robust insights into operational optimization, confirming both predictive accuracy and practical benefits for hospitality management. Occupancy forecasting results ($R^2 = 0.86$) indicate reliable demand prediction, enabling hotels to align staffing and guest services proactively (Ricaurte and Jagarajan, 2024). This accuracy supports revenue management strategies by reducing the risks of under- and over-staffing that erode profitability.

Energy optimization simulations yielded an average consumption reduction of 11.5%, closely matching post-implementation measurements within 1.2% of predicted values (Schick and Redlein, 2025). The high simulation accuracy (98.7%) demonstrates the viability of digital twin models for energy management, aligning with sustainability objectives and regulatory requirements set by European climate frameworks (European Commission, 2024). Operational integration of predictive HVAC controls and real-time monitoring fosters both cost savings and environmental performance improvements.

Workforce simulations achieved a 14.7% reduction in labor hours per occupied room, reflecting the digital twin's capacity to optimize staff allocation based on occupancy forecasts. These efficiency gains not only lower labor costs but also enhance service responsiveness by reducing staff idle time and workload variability (Feinstein and Parks, 2002). The technology complements human expertise by automating routine allocation tasks, allowing staff to focus on personalized guest interactions and value-added services.

Financial analysis confirms strong investment viability, with a 3.4-year payback period. The cumulative five-year benefit of €13,440 underscores the economic attractiveness of adopting digital twins. The investment case is further bolstered by non-financial benefits, including enhanced guest satisfaction through improved service consistency and proactive maintenance, which foster positive customer experiences and brand reputation.

Despite these promising findings, several implementation challenges warrant discussion. Initial capital requirements for platform licensing and IoT sensor deployment can strain budgets, particularly for smaller properties lacking existing digital infrastructure (Horecfex, 2025). Additionally, data integration complexities and interoperability issues between legacy property management systems and digital twin platforms require careful planning and technical expertise (XenonStack, 2023).

Organizational readiness and change management are critical for successful adoption. Staff training programs must include digital literacy and trust-building to ensure employees embrace simulation insights rather than resist technological guidance. Clear communication of performance benefits and alignment with strategic sustainability goals can mitigate resistance and foster stakeholder buy-in.

Future research should explore longitudinal impacts of digital twin integration, particularly regarding maintenance cost savings, guest loyalty metrics, and long-term environmental performance. Comparative analyses between centrally managed hotel chains and independent properties can reveal scalability factors influencing digital twin effectiveness. Additionally, integrating artificial intelligence modules for adaptive simulation refinement promises further improvements in accuracy and autonomous decision-support capabilities.

6. Conclusions

Digital twin technologies offer a transformative approach to hospitality management by enabling real-time simulation, predictive optimization, and data-driven decision support. This study demonstrates that simulation-based models can accurately forecast occupancy patterns ($R^2 = 0.86$), optimize energy consumption by 11.5%, and improve staff productivity by 14.7% across Central European hotels. Financial analysis confirms a 3.4-year payback period, validating the technology's economic viability.

The integration of digital twins aligns with Industry 5.0’s human-centric and sustainability objectives, balancing operational efficiency with personalized guest experiences and environmental stewardship (Maddikunta et al., 2022). Implementation challenges - including upfront investment, data integration, and organizational change - require strategic planning and stakeholder engagement to realize the full benefits.

By providing a concise, visualization-rich case study, this research offers practical guidance for hotel operators considering digital twin adoption. The demonstrated benefits underscore digital twins’ potential to enhance profitability, service quality, and sustainability performance in hospitality contexts. Future work should expand longitudinal analysis, explore AI-driven simulation refinements, and investigate scalability across diverse property types to further advance digital twin applications in the service sector.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Data Availability Statement

Publicly available datasets were analysed in this study. Energy consumption benchmarks can be found in Cornell Hotel Sustainability Benchmarking Index 2024 at https://ecommons.cornell.edu/items/85eddae3-2b5b-41fb-88ad-75a0b53f8424. Primary operational data from participating hotels is available on request from the corresponding author, subject to confidentiality agreements that protect proprietary business information and guest privacy. Simulation parameters and statistical analysis code are provided in supplementary materials upon reasonable request.

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Conflicts of Interest

The authors acknowledge the participating Central European hotels for data access and the institutional libraries for research resources.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve language quality and GitHub Copilot to optimize visualization code. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

Anshori, M. Y., Herlambang, T., Asyari, V., Arof, H., Firdaus, A. A., Oktafianto, K., & Suharto, B. (2024). Optimization of Hotel W Management through Performance Comparison of Support Vector Machine and Linear Regression Algorithm in Forecasting Occupancy. *Nonlinear Dynamics and Systems Theory, 24*(3), 228-235.

Arctiq. (2025). *The rise of cyber-physical systems*. Arctiq Blog. https://arctiq.com/blog/the-rise-of-cyber-physical-systems

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access, 7,* 167653-167671. https://doi.org/10.1109/ACCESS.2019.2953499

Build-UP EU. (2024). *Enhancing building energy performance with digital twin technologies: Insights from the SmartWins project*. Retrieved from https://build-up.ec.europa.eu/en/resources-and-tools/articles/enhancing-building-energy-performance-digital-twin-technologies

Chan, A. T. K., Wang, M., Brilakis, I., & Ip, N. M. Y. (2025, April). *Digital twin for sustainable hospitality facilities management: A review and empirical investigation*. ASCE. https://doi.org/10.17863/CAM.117392

Claroty. (2025a). *Bridging the gap: Cyber-physical system (CPS) security for hospitality*. Retrieved from https://claroty.com/blog/bridging-the-gap-cyber-physical-system-security-for-hospitality

Claroty. (2025b). *Cybersecurity for the hospitality industry*. Claroty Commercial Cybersecurity. https://claroty.com/commercial-cybersecurity/hospitality

Edelheim, J. R., & Ueda, D. (2007). Effective use of simulations in hospitality management education-a case study. *Journal of Hospitality, Leisure, Sport and Tourism Education,* 6(1), 18-28. https://doi.org/10.3794/johlste.61.104

Eiada, R. R., Elabasy, M. M., Abdelrasheed, S. A., Elhmady, N., & Elshahat, D. R. (2025). Integrating digital twin technology in energy management: A review of smart building solutions. *Journal of Engineering Research and Reports,* 27(4), 354-360. https://doi.org/10.9734/jerr/2025/v27i41477

European Commission. (2024). *Industry 5.0. Research and Innovation*. Retrieved from https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en

Feinstein, A. H., & Parks, S. J. (2002). Simulation research in the hospitality industry. In *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL conference* (Vol. 29), 45-57.

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: enabling technologies, challenges and open research. *IEEE Access, 8*, 108952-108971. https://doi.org/10.1109/ACCESS.2020.2998358

Hariharasitaraman, S., Yadav, R., & Agrawal, P. (2023). Some Insights of Cyber Physical Systems in the Context of the Tourism and Travel Industry: A Blockchain-Based Smart Framework for Smart Services. In *Handbook of Research on Data Science and Cybersecurity Innovations in Industry 4.0 Technologies* (pp. 357-379). IGI Global. https://doi.org/10.4018/978-1-6684-8145-5.ch018

He, B., & Bai, K. J. (2021). Digital twin-based sustainable intelligent manufacturing: A review. *Advances in Manufacturing, 9*(1), 1-21. https://doi.org/10.1007/s40436-020-00302-5

Horecfex. (2025). *Digital twin in hospitality marks the dawn of limitless operations*. Retrieved from https://horecfex.com/en/digital-twin-in-hospitality-dawn-of-limitless-operations/

Hwang, J., Kim, J., & Yoon, S. (2025). DT-BEMS: Digital twin-enabled building energy management system for information fusion and energy efficiency. *Energy, 326*, 136162. https://doi.org/10.1016/j.energy.2025.136162

Javaid, M., Haleem, A., & Suman, R. (2023). Digital twin applications toward Industry 4.0: A review. *Cognitive Robotics, 3*, 71-92. https://doi.org/10.1016/j.cogr.2023.04.003

Joglekar, S., Kadam, S., & Dharmadhikari, S. (2023). Industry 5.0: Analysis applications and prognosis. *The Online Journal of Distance Education and e-Learning, 11*(1), 257-264.

Jradi, M., & Bjornskov, J. (2023, July). A digital twin platform for energy efficient and smart buildings applications. In *2023 Fifth International Conference on Advances in Computational Tools for Engineering Applications (ACTEA)* (pp. 1-6). IEEE. https://doi.org/10.1109/ACTEA58025.2023.10194071

Lu, Y., Liu, C., Kevin, I., Wang, K., Huang, H., & Xu, X. (2020). Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and computer-integrated manufacturing, 61*, 101837. https://doi.org/10.1016/j.rcim.2019.101837

Lvov, S. (2025). *Transforming hospitality: Implementing digital twins in the hotel industry*. LinkedIn Pulse. Retrieved from https://www.linkedin.com/pulse/transforming-hospitality-implementing-digital-twins-hotel-sergei-lvov-cgk9e

Maddikunta, P. K. R., Pham, Q. V., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. *Journal of Industrial Information Integration, 26*, 100257. https://doi.org/10.1016/j.jii.2021.100257

MarketIntelo. (2025). *Digital twin for hospitality market research report 2033*. Retrieved from https://marketintelo.com/report/digital-twin-for-hospitality-market

Nahavandi, S. (2019). Industry 5.0 - A human-centric solution. *Sustainability, 11*(16), 4371. https://doi.org/10.3390/su11164371

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing, 11*, 939-948. https://doi.org/10.1016/j.promfg.2017.07.198

Neuron Cloud. (2024). *Digital twin for hotels: Unlocking visual data to power sustainable hospitality*. Retrieved from https://www.neuroncloud.ai/digital-twin-for-hotels-hospitality/

Peng, X., Zhu, J., Lee, S., Zhou, D., Song, W., & Ying, T. (2024). Digital transformation in the hospitality industry: A bibliometric review from 2000 to 2023. *International Journal of Hospitality Management, 120*, 103761. https://doi.org/10.1016/j.ijhm.2024.103761

Pylianidis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. *Computers and Electronics in Agriculture, 184*, 105942. https://doi.org/10.1016/j.compag.2020.105942

Rame, R., Purwanto, P., & Sudarno, S. (2024). Industry 5.0 and sustainability: An overview of emerging trends and challenges for a green future. *Innovation and Green Development, 3*(4), 100173. https://doi.org/10.1016/j.igd.2024.100173

Ricaurte, E., & Jagarajan, R. (2024). Hotel Sustainability Benchmarking Index 2024: Carbon, energy, and water. *Cornell Hospitality Report, 24*(10) (May 2024), 1-38. https://hdl.handle.net/1813/115166

Sayed, A. N., Bensaali, F., Himeur, Y., Dimitrakopoulos, G., & Varlamis, I. (2025). Enhancing building sustainability: A Digital Twin approach to energy efficiency and occupancy monitoring. *Energy and Buildings, 328*, 115151. https://doi.org/10.1016/j.enbuild.2024.115151

Schick, A. (2024). Reporting metrics and benchmarking results in hotel energy consumption: A systematic literature review (SLR). *Journal for Facility Management, 1*(26), 32-54. https://doi.org/10.34749/jfm.2024.4683

Schick, A., & Redlein, A. (2025). Energy consumption intensity indicators and sustainability benchmarking in the hotel industry: Perceptions of stakeholders in the DACH region. In *CIB Conferences* (Vol. 1, No. 1, p. 310). https://doi.org/10.7771/3067-4883.1776

Semeraro, C., Biyrouti, S. J. A., Abdelkareem, M. A., & Olabi, A. G. (2025). Digital twin-driven innovation in smart and green building: a structured review and research agenda. *International Journal of Thermofluids, 101393*. https://doi.org/10.1016/j.ijft.2025.101393

TWI Global. (2021). *What is Industry 5.0? (Top 5 Things You Need To Know)*. Retrieved from https://www.twi-global.com/technical-knowledge/faqs/industry-5-0

Twinview. (2025). *The intelligent hotel: Navigating costs with digital twins*. Retrieved from https://www.twinview.com/insights/the-intelligent-hotel-navigating-costs-with-digital-twins

XenonStack. (2023). *Understanding cyber-physical systems (CPS) and their elements*. XenonStack Insights. https://www.xenonstack.com/insights/cyber-physical-systems

Zaki, K. G. (2019). Using the mixed methods research to model the hotel performance measurement in Egypt: An example from a hotel chain. *Journal of Global Business Insights, 4*(1), 18-33. https://www.doi.org/10.5038/2640-6489.4.1.1054

Zhao, Z. (2025, March). Design of Smart Building Energy Management System Based on Digital Twin Technology. In *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)* (Vol. 259, p. 192). Springer Nature. https://doi.org/10.2991/978-94-6463-658-1_19