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Impact of Digital Twinning in the Retrofitting of Healthcare Infrastructure

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Abstract

Retrofitting healthcare facilities to suit the changing requirements and industry standards is a crucial endeavour. Against this background, integrating digital twinning technology has become a viable way to transform the retrofitting procedure. This study explores the significant influence of digital twinning on the renovation of healthcare facilities, illuminating the revolutionary possibilities of this creative strategy. Real-time observation, analysis, and simulation of a healthcare facility's structural and operational elements are made possible by digital twinning technology, which builds a virtual image of the real thing. This paper investigates the many consequences of digital twinning within healthcare infrastructure retrofitting through an extensive assessment of the literature, analysis, and evaluation of real-world implementations. According to the research, digital twinning could completely change how healthcare infrastructure is maintained and updated. By providing a virtual representation of the physical space, healthcare administrators can model, optimize, and continuously monitor the systems and layout of the facility, which eventually leads to increased operational efficiency. It also makes it easier to find areas where costs can be cut, enhances the way patients are cared for, and guarantees that the ever-changing rules and guidelines governing healthcare are strictly followed.

Keywords: Digital twinning, Internet of Things (IoT), Retrofitting, Healthcare Infrastructure, Construction manufacturing

INTRODUCTION

As a transformative technology in the era of Industry 4.0, DTs are reshaping industries through the use of cutting-edge digital technologies to produce virtual copies of real-world objects and processes. They are used in many different industries, such as construction, manufacturing, healthcare, and transportation. With their ability to improve planning, design, simulation, real-time monitoring, predictive maintenance, and stakeholder collaboration, DTs have enormous potential for the construction industry. In the construction industry, digital twins, or virtual replicas of real assets, systems, or procedures, are called digital representations or DTs.

They gather and track real-time data about the physical counterpart using a variety of data sources, such as sensors, Internet of Things (IoT) devices, and other technologies (Kumar, Basu, & Paul, Utilization of Floats in Project Schedule Recovery- A Pilot Schedule Demonstration, 2020). [7] The goal of DTs is to make it easier to simulate, analyze, and optimize the performance of the physical asset, which will improve decision-making, maintenance forecasting, and overall project efficiency. DTs are a crucial component of Industry 4.0 systems, which are digital models meant to accurately depict tangible objects or

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systems. DTs were first applied in the aerospace industry Paul, V. K., Basu, C., Rastogi, A., & Kumar, K. (2021).[9] They are still utilized today in many different industries, such as meteorology, industrial manufacturing, construction, healthcare, aviation and autos, education, and the development of smart cities and entire nations.

DTs are used to evaluate the performance of developed products or to remodel physical objects that already exist. Prognostics, design, manufacturing, and health management were among the industrial uses of DTs that were most prevalent. In contrast, several industries, such as oil and gas, aerospace, construction, and automotive, have been using simulation techniques for many years Paul, V. K., Basu, C., Rastogi, A., & Kumar, K. (2022).[10] The real-time simulation capabilities of DTs, which are based on conventional simulation techniques like discrete and continuous event simulation, offer a wide range of additional applications. For example, DTs have been used in continuous facilities in the food, pharmaceutical, and petrochemical sectors; in the latter two, they have also been used in small-batch and large-batch cement production. Paul, V., & Kumar, K. (2021) [11] Pragya, & Kumar, K. (2021) [12] Furthermore, identified three types of digital models: twins, shadows, and digital models. Digital models, which are commonly employed in fields like architecture, engineering, and design (AEC), are computer-generated representations of real-world objects or systems. In computer graphics and video games, shadows are visual effects that replicate the way light interacts with things (Harit & Kumar, 2021)[2] (Kumar & Nayal, Critical Review of use of Glass Fiber Reinforced Gypsum (GFRG) Panels in Housing in India, 2020). [3] Conversely, in the digital age, the phrase "twins" needs more context to fully grasp its meaning.

Lately, DTs have been used in construction using data from several sources, such as sensors, Building Information Modeling (BIM) software, and Internet of Things (IoT) devices, DTs are virtual copies of actual assets, such as infrastructure or buildings. DTs are often employed during construction to imitate the construction process, enhance design, find potential problems, and track a building's performance over time. A DT, for instance, may evaluate various building techniques and forecast the effects they will have on the building's energy usage, structural soundness, and general sustainability. Nevertheless, there is still a dearth of experience with DT used in constructing. Although digital transformation technologies are relatively new, their utilization requires a diverse range of specialized skills in fields such as software development, data analytics, and building and construction management.

LITERATURE REVIEW

Definition and Components of DT's

DTs provide for real-time monitoring, analysis, and simulation since they are virtual copies of real things. They consist of several essential components, including data integration, modelling and simulation, analytics, and visualization. While modelling and simulation provide a virtual picture of the real system, data integration includes combining data from several sources. DTs are useful in a variety of industries and provide advantages including enhanced operational effectiveness, preventative maintenance, and assistance with decision-making.

Application of DT's in Construction

In building operations and maintenance, DTs are defined as merging static and dynamic BIM models. Construction management workflows utilizing deep learning (DT) integrate sensors, the Internet of Things, semantic web technologies, and advanced algorithms and artificial intelligence (AI) to monitor and control project development and construction. Similarly, DTs and Cyber-Physical Systems (CPS) serve as a bridge between the realms of the actual and virtual. Two distinct but connected ideas that revolutionize the way we test, create, and oversee physical systems are DT and CPS. DTs, or virtualized versions of real systems, are useful for predictive analytics, optimization, and simulation. Real-time monitoring and control are made possible by CPSs, which are physical systems that are closely connected to digital systems. Providing monitoring and control in real-time is one of the main advantages of DTs and CPSs. As a result, possible issues may be quickly identified and addressed, boosting productivity and decreasing downtime. Simulating and optimizing physical systems to increase efficiency and save costs is an additional benefit. However, there may be worries about cybersecurity and data privacy, and these technologies also necessitate a large investment in digital technology. DTs make passive control possible because they can predict the state of the physical model in the future. By use of devices such as actuators, the cyber model in CPS is connected to the physical model passively or actively, hence regulating the state of the physical system.

Using wearable sensors, VIVE Trackers, machine learning, and virtual reality, construction workers may also receive training on reducing accidents. Using sensors and Internet of Things technologies, the DT's framework supported the digital supply chain and revealed information on the fill level of silos holding building materials. Planners can reduce building materials, transportation costs, and time by using the suggested methodology to track and move silos in real-time.

BENEFITS AND LIMITATIONS OF DT's

Digital twins, or virtual copies of real-world objects or systems, offer several benefits in a variety of sectors. Proactive decision-making and increased operational efficiency are made achievable by real-time monitoring and analysis. Predictive maintenance capabilities reduce downtime and optimize maintenance schedules (Kumar, Basu, & Paul, Utilization of Floats in Project Schedule Recovery- A Pilot Schedule Demonstration, 2020). [7] Optimization and simulation allow for process and design improvements, while enhanced product development supports faster time-to-market. Better decision-making also becomes achievable by digital twins' comprehensive insights. Nevertheless, DTs encounter difficulties such ascomplicated data integration, expensive implementation, privacy and security worries, problems with data accuracy, and adoption barriers (Sharma & Kumar, 2022).[15] Tofully utilize DTs and realize their benefits across sectors, these constraints must beaddressed.

INTRODUCTION TO RETROFITTING

Retrofitting is a process of making improvements or modifications to an existing structure, system, or component to enhance its performance, functionality, safety, energy efficiency, or compliance with new standards or regulations (Radwana, 2016) [13] (Kumar & Paul, A Critical Review of Risk Factors and Reliability Assessment Issues of Fire and Life Safety in Buildings, 2022).[4] It is commonly applied to buildings, infrastructure, and machinery. Retrofitting is an important aspect of sustainable construction and maintenance, as it can extend the useful life of existing structures and reduce the requirement for comprehensive replacements, which can be costly and resource-intensive (Kumar K. , Basu, Rastogi, & Paul, 2020). [8]

Key Aspects and Objectives of Retrofitting Include

1. *Enhancing Safety:* Retrofitting can make structures more resilient to natural disasters such as earthquakes, floods, and hurricanes. This involves strengthening the building's structural elements to withstand these forces.
2. *Improving Energy Efficiency:* Many older buildings were constructed before modern energy efficiency standards were in place. Retrofitting can involve adding insulation, upgrading windows, or installing energy-efficient HVAC systems to cut operating expenses and energy use.
3. *Upgrading Technology:* Retrofitting can include upgrading outdated systems and equipment to the latest technology. This is often seen in industrial settings where machinery and control systems are modernized for improved performance and safety.
4. *Compliance With Codes and Regulations:* Building laws and guidelines are updated over time. Retrofitting may be necessary to bring older structures into compliance with current safety, accessibility, or environmental standards.
5. *Adapting To Changing Needs:* Retrofitting allows structures to adjust to evolving requirements. For example, an office building may be retrofitted to accommodate open-plan workspaces, or a

warehouse may be retrofitted to serve a different purpose.

6. *Preservation Of Historic Structures:* Retrofitting is often employed in the preservation of historic buildings. It involves carefully modifying the structure to make it suitable for modern use while preserving its historical and architectural value.

The specific methods and techniques used in retrofitting depend on the type of structure or system being modified and the objectives of the retrofit. Common retrofitting techniques include the addition of reinforcement materials like steel or carbon fibre, the installation of new systems or components, and the removal or replacement of outdated elements.

DIGITAL TWINS: TRANSFORMING RETROFITTING

Digital twin technology offers a revolutionary method of retrofitting by offering a thorough and dynamic virtual representation of the structure. Real-time data and information are integrated into this model from several sources, such as:

- *Geometric data:* 3D models of the building's structure and layout.
- *Operational data*: Energy consumption, water usage, occupant behaviour, etc.
- *Performance data:* Structural integrity, equipment health, system efficiency, etc.
- *Environmental data*: Climate conditions, air quality, etc.

By combining this data in a single platform, digital twins enable stakeholders to:

- Examine and visualize the building's existing condition, looking for areas that might want renovation as well as any shortcomings.
- Simulate and predict the impact of various retrofitting interventions, including energy savings, cost-effectiveness, and occupant comfort.
- Optimize design solutions based on a thorough comprehension of the building's functionality.
- Prioritize and schedule maintenance activities based on real-time data and predictions.
- Monitor the performance of retrofitted systems and identify areas for further improvement.

CURRENT HEALTHCARE INDUSTRY OVERVIEW

The modern healthcare sector is becoming increasingly complicated, and many healthcare facility managers are finding it difficult to provide a safe healthcare environment. Every day, a large number of facilities and medical data are processed in a hospital environment to ensure smooth operations. Most of the facility information, nonetheless, is unrelated to the process of providing healthcare. It is error-prone and frequently processed manually. From the standpoint of patient safety, facility information must be integrated with the healthcare delivery process (Kumar & Paul, Significance of Fire Protection System Reliability for Structure Fire Safety, 2023) [6] Kumar, K., & Paul, V. K. (2022) [5] (Roy, Kumar, & Paul, 2023) [14] (Kumar K. , Basu, Rastogi, & Paul, 2020).[8] There have been significant changes in social, organizational, political, economic, and cultural aspects of healthcare delivery in the United States. Similarly, the healthcare sector is under greater regulatory pressure than any other sector because of rising prices and expectations.

Retrofitting Healthcare Facilities

Healthcare institutions are expanding, renovating, retrofitting, and refurbishing more often. It should be mentioned that hospitals prioritize emergency rooms, imaging centres, surgical rooms, and cancer centres, and improving infrastructure when undertaking remodelling and extension projects to better serve patients and facilitate the usage of IT. Retrofitting and renovating healthcare facilities is difficult and frequently disruptive to patients, staff, and their daily work responsibilities because hospitals must run around the clock. while building a facility within or adjacent to an operational hospital, it is especially important to pay great attention to healthcare standards and patient safety regulations while retrofitting healthcare facilities (Paul V. K., Basu, Rastogi, & Kumar, 2022) [8] (Roy, Kumar, & Paul, 2023). [14]

Patient Safety Considerations During the Retrofit Process

Retrofitting and renovation of hospital projects present various challenges for patients and staff. Early input from infection control and safety specialists is necessary to guarantee patient safety and prevent interruptions to care services. The Joint Commission and CMS (Centres for Medicare & Medicaid Services) mandate that healthcare institutions that accept Medicare payments perform ICRAs (Infection Control Risk Assessments). When hospital facilities need to be retrofitted or renovated to meet patient safety regulations, ICRA is used. To lower the patient risk of HAIs, the ICRA offers guidelines for retrofit and renovation projects at every stage (Kumar K. , Basu, Rastogi, & Paul, 2020) [8] (Das, Rastogi, & Kumar, 2021). [1] When hospitals undergo renovations, maintenance, or construction, dust or waterborne fungi or bacteria are released into the air and cause HAIs.

GAP ANALYSIS

An increasing focus on measures to enhance patient safety within the environment of care has led many healthcare providers to evaluate the extent to which their facilities address this need. Unfortunately, many existing facilities due to their age, dated design approaches, technology, and other requirements are unable to address this and often struggle to cope with increasingly stringent standards for patient safety. As a result, implementing new technology is extremely difficult, and many healthcare professionals are finding it harder and harder to offer a safe healthcare environment (Kumar & Paul, Risk and Reliability Assessment of Smoke Control Systems in the Buildings, 2022) [5] (Paul & Kumar, 2021). [6 Refitting healthcare facilities is the way to get past these obstacles and give them a chance to abide by new rules and regulations. A lot of healthcare facilities use a variety of practical short-term fixes to deal with these issues, but they are only partially successful. While new projects were delayed or reviewed due to the recession and new laws, construction projects in the healthcare sector increased marginally in 2011. Of these, 73% involved the retrofitting or renovation of hospital projects. Retrofitting these facilities to satisfy both present demands and anticipated future needs is a more practical course of action. While doing this, it would be wise to incorporate facility management improvement strategies into the retrofit project, thus there might be a large cost reduction through this approach. There are several obstacles to overcome while retrofitting a healthcare facility, especially when it comes to preserving patient safety during the project's duration and ensuring healthcare delivery operations.

RESEARCH AIM AND OBJECTIVES

This study aims to examine ways to remodel healthcare facilities such that energy efficiency and patient safety are improved at the same time by integrating the concept of Digital twins. The specific objectives include:

- To look into information flows and overlaps between the process of providing healthcare and facilities management.
- To establish requirements for retrofitting healthcare facilities to enhance patient safety and improve programming schedules by DTs.
- To investigate current approaches to healthcare facility retrofits including mechanisms for ensuring patient safety before, during, and after retrofit works in healthcare facilities.
- To characterize the critical digital twinning opportunities and develop mechanisms and systems for implementing these.
- To identify and model critical patient safety issues that need to be addressed in the retrofitting healthcare facilities.

DIGITAL TWINNING IN HEALTHCARE INFRASTRUCTURE

Digital twinning represents a revolutionary development in the healthcare sector, particularly in the management of healthcare facilities. The concept revolves around the construction of a virtual equivalent of a medical facility, offering a virtual counterpart that mirrors every aspect of the real-world facility (Pragya & Kumar, 2021) (Kumar K. , Basu, Rastogi, & Paul, 2020).[8] This digital twin not only captures the static physical elements but also dynamically synchronizes with real-time data, facilitating accurate simulations and ongoing observation.

One of the primary benefits is the ability to optimize patient care. Healthcare facilities can use digital twins to monitor patient experiences and the efficiency of healthcare delivery, making real-time adjustments to enhance patient satisfaction and the quality of care. Additionally, predictive maintenance, made possible through digital twinning, can ensure that medical equipment operates at peak efficiency, reducing downtime and enhancing the overall quality of service.

Operational efficiency is another significant advantage. Digital twins enable healthcare facilities to analyse and improve workflows, resource allocation, and the utilization of space. With real-time data at their disposal, healthcare administrators and facility managers can make data-driven decisions to streamline operations and improve overall efficiency. This is crucial in an environment where every second can make a difference in patient outcomes.

Furthermore, digital twinning possesses the capability to enhance the resilience of healthcare facilities. In the face of unforeseen challenges, whether they be natural disasters or public health emergencies, the ability to simulate and prepare for such events can be a game-changer. By creating virtual disaster scenarios and running simulations, healthcare facilities can fine-tune their response strategies, ensuring the safety of patients and staff.

However, it is not without its challenges. Data security and patient privacy are paramount concerns when working with sensitive healthcare information. Additionally, ensuring interoperability with the diverse array of medical equipment, sources of data, and systems in a healthcare facility can be complex. Workforce readiness, in terms of training and skills, is also crucial to harness the full potential of digital twinning.

In conclusion, digital twinning in healthcare facilities is poised to transform the way we manage healthcare delivery. It offers the promise of improving patient care, enhancing operational efficiency, and fortifying facility resilience. While challenges exist, the application of this technology is reshaping the landscape of healthcare management, ultimately contributing to better patient outcomes and a more efficient, responsive healthcare system.

IMPLEMENTATION OF DTS DIGITAL TWINNING IN RETROFITTING IN HOSPITALS

Digital twinning in retrofitting has unique and significant impacts when applied to hospitals and healthcare facilities. These impacts extend beyond just the physical infrastructure, influencing patient care, safety, and overall operational efficiency. Here are some key impacts of digital twinning in retrofitting hospitals:

1. *Enhanced Patient Care:* Digital twinning allows for the optimization of patient care environments. It enables the redesign and reconfiguration of patient rooms, waiting areas, and treatment spaces to improve patient comfort, privacy, and accessibility. The health and recuperation of the patient may directly benefit from this.
2. *Improved Workflow Efficiency:* Digital twinning helps identify bottlenecks and inefficiencies in healthcare facility workflows. By analysing how staff, patients, and resources move within the hospital, retrofits can be planned to streamline the delivery of care, reduce wait times, and enhance operational efficiency (Kumar K. , Basu, Rastogi, & Paul, 2020).[8]
3. *Energy Efficiency:* Hospitals are known for their high energy consumption. Digital twinning enables the integration of energy-efficient systems and equipment, such as LED lighting, intelligent HVAC systems, and renewable energy sources. This results in cost savings and a reduced carbon footprint.
4. *Resilience to Disaster and Emergency Situations:* Hospitals must remain operational during emergencies and disasters. Digital twinning allows for simulations of various disaster scenarios,

helping hospitals retrofit to withstand seismic events, floods, and other emergencies. It also helps plan for effective evacuation routes and resource allocation during crises.

5. *Advanced Medical Equipment Integration:* Digital twinning allows for the seamless integration of advanced medical equipment into hospital environments. This includes the installation of state-of-the-art diagnostic and monitoring devices, telemedicine capabilities, and the implementation of smart healthcare systems.
6. *Patient Privacy and Security:* Digital twinning technology may also be used to guarantee patient data privacy and security during the refit process, particularly when installing sophisticated technological solutions, as sensitive patient data becomes more digitalized.
7. *Compliance with Healthcare Regulations:* Digital twinning facilitates compliance with evolving healthcare regulations, ensuring that the retrofit aligns with the latest standards related to patient safety, accessibility, infection control, and fire safety.
8. *Remote Monitoring and Telemedicine:* In the wake of the COVID-19 pandemic, telemedicine and remote patient monitoring have become more essential. Digital twinning supports the integration of telehealth solutions, enabling healthcare facilities to expand services to remote areas and providing more flexible care options for patients.
9. *Cost Savings:* By identifying areas of inefficiency and waste, digital twinning helps hospitals reduce operational costs in the long term. The technology enables predictive maintenance and asset management, which prevents costly unexpected equipment failures.
10. *Adaptive Retrofitting:* Healthcare needs and technologies continue to evolve. Digital twinning allows healthcare facilities to adapt and reconfigure spaces, ensuring they remain relevant and capable of providing the best care to patients.

To sum up, digital twinning has a variety of positive effects on hospital retrofitting, including improved patient care, operational effectiveness, energy efficiency, and resistance to disasters. In addition to enhancing patient and staff safety and well-being, this technology also lets healthcare institutions take advantage of the opportunities presented by the rapidly evolving healthcare industry.

KEY PERFORMANCE INDICATORS (KPI's) FOR DIGITAL TWIN-BASED HOSPITAL RETROFITTING

To evaluate the efficacy of digital twin technology in hospital retrofitting, an extensive array of Key Performance Indicators (KPIs) spanning several aspects is necessary.

Table 1. Key Performance Indicators (KPIs) for Digital Twin in Hospital Retrofitting.

Category	KPI	Description	Target	Measurement Tools	Frequency
Efficiency & Cost Optimization	Energy Consumption Reduction	% decrease in energy consumption after retrofitting	15% - 30%	Utility bills, BMS data, digital twin model simulations	Monthly, quarterly, yearly
	Operational Cost Reduction	% decrease in operational costs (e.g., energy, maintenance, cleaning) after retrofitting	10% - 20%	Financial records, maintenance logs, digital twin model simulations	Monthly, quarterly, yearly
	Maintenance Efficiency Improvement	% decrease in reactive maintenance and % increase in preventive maintenance	20% reduction in reactive, 10% increase in preventive	Maintenance records, CMMS data, digital twin model predictions	Monthly, quarterly, yearly
Patient Care & Comfort	Occupant Comfort Improvement	% of occupants satisfied with the indoor environment (temperature, air quality, lighting)	80% - 90%	Occupant surveys, sensor data, digital twin model simulations	Quarterly, yearly
	Reduction in HAI Rates	Rate of HAIs per 1000 patient days	5% - 10% reduction	Infection control data, digital twin model analysis of environmental factors	Quarterly, yearly

	Patient Outcome Improvement	% reduction in readmission rates, length of stay, mortality rates	5% - 10% reduction	Patient records, medical data, digital twin model simulations	Quarterly, yearly
Environmental Impact	GHG Emissions Reduction	% decrease in greenhouse gas emissions (e.g., CO_2)	10% - 20%	Energy consumption data, digital twin model simulations, environmental monitoring data	Monthly, quarterly, yearly
	Resource Consumption Reduction	% decrease in water and waste generated	10% - 15%	Meter readings, waste disposal records	Monthly, quarterly, yearly
Technology Adoption & Utilization	Digital Twin Model Accuracy	% of actual data points within the predicted range of the model	80% - 90%	Continuous comparison of real-time data with model predictions	Continuous
	User Adoption & Engagement	% of stakeholders actively using the digital twin platform	70% - 80%	User login data, platform usage statistics, surveys	Monthly, quarterly, yearly
	ROI	The ratio of benefits gained from retrofitting to the cost of digital twin solution	2:1 - 5:1	Financial analysis, project cost data, performance data	Yearly

CONCLUSION

This study explored the extensive and diverse effects of digital twinning in hospital retrofitting, highlighting its revolutionary potential for the medical field. The findings conclusively demonstrate that digital twinning is a new paradigm that significantly enhances patient care, operational efficiency, sustainability, and resilience within healthcare institutions, transcending its status as a mere technological innovation.

Key Takeaways

- Digital twinning provides a wide array of benefits for hospital remodelling all geared towards improving healthcare delivery.
- Patient-centric design streamlined processes and integration of advanced medical technology contribute to enhanced patient care.
- Increased patient comfort privacy and accessibility lead to improved experiences and outcomes.
- Operational efficiency is a key advantage allowing hospitals to optimize workflow reduce wait times and manage resources effectively.
- Environmental sustainability is addressed through the integration of energy-efficient equipment and systems lowering energy use and providing enduring financial gains.
- Digital twinning improves hospital resilience through disaster planning and simulations equipping hospitals to handle crises and natural disasters and ensuring the safety of patients and staff during critical moments.
- Adaptability to evolving healthcare standards is evident through positive impacts on patient privacy and security regulatory compliance and data protection requirements.
- Cost savings are achieved through predictive maintenance, asset management and streamlined operations, leading to lower long-term operational expenses.
- Meeting evolving healthcare demands and reaching underserved areas are facilitated by integrating telehealth and remote patient observation offering more flexible and comprehensive care options.
- Future-proofing healthcare facilities is achieved through enabling adaptation and reconfiguration of spaces to remain relevant and responsive to changing needs.

Overall

Digital twinning represents a game-changer for hospital renovations, impacting not just infrastructure but the very core of healthcare delivery. This transformative technology paves the pathway to a healthcare landscape characterized by enhanced patient care, operational excellence, sustainability, and resilience. Embracing digital twinning in hospital retrofitting is crucial for ensuring the safety, well-being, and future readiness of healthcare facilities. As healthcare continues to evolve, digital twinning will play an increasingly vital role in shaping the healthcare infrastructure of tomorrow.

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