Applied Artificial Intelligence Research

INNOVIAIR

A Closed-Loop Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery: Integrating Environmental Assessment, Risk Prediction, and Adaptive Resource Management

Jinghan Li[a,*]

[a]School of Business and Management, Lincoln University College, Petaling Jaya 47301, Selangor, Malaysia

ARTICLEINFO

Keywords:
Digital Twin
Post-Disaster Urban Recovery
Urban Resilience
Environmental Risk
Chemical Risk
Sustainable Resource Management
Adaptive Decision Support

ABSTRACT

Natural disasters, climate change, and rapid urbanization have increased the complexity of post-disaster urban recovery, creating challenges in environmental management, risk mitigation, and resource allocation. Conventional recovery approaches often rely on fragmented information and relatively fixed decisions, limiting their ability to respond to changing environmental and recovery conditions. This study proposes a Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR) that integrates multisource urban data, environmental quality assessment, chemical-risk-aware prediction, sustainable resource management, and adaptive decision support. A Chemical Risk-Aware Digital Twin Environmental Risk Prediction Module (CR-DT-ERP) is incorporated to capture evolving chemical-related environmental risks and connect risk information with recovery strategy evaluation and resource allocation. The framework establishes a closed-loop process linking environmental and infrastructure assessment, digital twin state updating, recovery strategy evaluation, resource allocation, recovery actions, and feedback. A controlled synthetic post-earthquake scenario is developed to demonstrate the framework over a 30-day recovery period. Three recovery strategies are compared under common initial conditions and resource constraints: rapid restoration-oriented recovery, sustainability-oriented recovery, and digital twin-based adaptive recovery. The results indicate that the adaptive strategy achieves a more balanced performance across recovery effectiveness, environmental performance, resilience, chemical risk, and resource consumption, rather than maximizing a single objective. The study extends digital twin applications from conventional monitoring toward adaptive and risk-aware post-disaster recovery coordination. The proposed framework provides a structured basis for integrating environmental risks, resource constraints, and resilience objectives into sustainable urban recovery planning.

1.Introduction

1.1.Background

Natural disasters, including earthquakes, floods, hurricanes, wildfires, and extreme climate events, have become increasingly frequent and severe worldwide, creating growing challenges for sustainable urban development and resilient city governance. Rapid urbanization, increasing interdependence among infrastructure systems, and climate-related pressures have further increased the vulnerability of urban environments. As a result, post-disaster recovery is no longer limited to restoring damaged infrastructure and public services. It increasingly involves environmental restoration, resource coordination, ecological protection, and the long-term improvement of urban resilience[1,2].

Beyond direct physical damage, disasters can generate substantial environmental consequences, including deterioration of air and water quality, soil contamination, ecosystem disruption, and the release of hazardous substances. Such impacts may continue throughout the recovery period and can interact with infrastructure reconstruction and human activities. Environmental conditions therefore need to be considered together with infrastructure functionality, resource availability, and recovery priorities when developing sustainable post-disaster strategies[3–5].

* Corresponding author.
E-mail address: jinghan.phdscholar@lincoln.edu.my.
https://doi.org/10.65455/2e987122
Received 3 August 2026; Received in revised form 21 August 2026; Accepted 21 August 2026; Available 28 August 2026

Traditional post-disaster recovery approaches often rely on fragmented information sources, periodic assessments, and sector-specific management practices. Although such approaches can provide useful support for emergency response and reconstruction, they are less effective when environmental conditions, infrastructure functionality, resource availability, and secondary risks change over time. Resilience-oriented recovery consequently requires more flexible approaches capable of linking changing system conditions with recovery decisions and resource allocation[1,2,5,6].

Recent developments in digital technologies have created new opportunities for addressing these challenges. Digital Twin (DT) technology provides a mechanism for establishing a dynamic connection between physical systems and their virtual representations. In urban applications, digital twins can integrate heterogeneous information from sensors, Geographic Information Systems (GIS), remote sensing, infrastructure databases, and other digital sources to support monitoring, simulation, prediction, and decision-making[7–10]. The broader development of smart-city and real-time urban management has also demonstrated the value of continuous data integration for understanding complex urban systems and supporting adaptive governance[11–13].

The analytical capabilities of digital twins have continued to develop beyond basic monitoring and visualization. Existing research has examined their use in predictive maintenance, system performance assessment, lifecycle management, and data-driven decision support[14–17]. Digital twin research has also expanded to cyber-physical production systems, where connected digital representations support system monitoring and operational improvement[18]. In parallel, smart-city research has emphasized digital integration, data-driven urban analysis, and real-time management as important foundations for more adaptive urban governance[19–21]. Recent studies published in Applied Artificial Intelligence Research have further demonstrated the use of multimodal sensor data, explainable machine learning, predictive maintenance, and digital twin architectures for intelligent system assessment and operational decision support[22–24]. These developments indicate that digital twins can serve not only as representations of physical systems but also as analytical environments for evaluating changing system conditions and supporting alternative decisions.

However, the application of digital twins to post-disaster urban recovery remains relatively fragmented. Existing studies have largely concentrated on infrastructure monitoring, damage assessment, predictive maintenance, or the optimization of individual operational tasks[7–10,14–17]. Comparatively less attention has been given to an integrated recovery framework that simultaneously considers environmental quality, environmental risk, sustainable resource management, and adaptive recovery decisions.

Chemical-related environmental risks represent a particularly important dimension of this problem. Earthquakes and other disasters may damage industrial facilities, hazardous-material storage systems, pipelines, and other infrastructure, resulting in pollutant release and subsequent environmental risks. During the recovery period, these risks may evolve as a consequence of contaminant migration, environmental attenuation, reconstruction activities, and intervention measures. Existing digital twin applications have demonstrated strong capabilities in monitoring and prediction, but the dynamic integration of chemical-related environmental risk into post-disaster recovery decision-making remains insufficiently developed.

To address this gap, this study proposes a Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR). The framework integrates environmental quality assessment, chemical-risk-aware environmental prediction, sustainable resource management, and intelligent decision support within a unified digital twin architecture. In particular, the framework introduces a Chemical Risk-Aware Digital Twin Environmental Risk Prediction Module (CR-DT-ERP) to connect evolving chemical risk with recovery strategy evaluation and resource allocation. The proposed framework is subsequently examined through a controlled synthetic post-earthquake scenario involving infrastructure recovery, environmental conditions, chemical-risk evolution, and resource constraints.

The remainder of this paper is organized as follows. Section 2 reviews research on urban resilience, digital twins, smart urban governance, and digital twin applications relevant to disaster recovery. Section 3 presents the proposed DT-SRUR framework and its methodological components. Section 4 provides a synthetic post-earthquake scenario simulation and computational comparison of three recovery strategies. Section 5 discusses the theoretical and practical implications, limitations, and future research directions. Section 6 concludes the study.

1.2.Research gap

Although digital twin technology has been increasingly applied in smart-city management, infrastructure monitoring, predictive maintenance, and intelligent decision support, several gaps remain in the context of sustainable post-disaster urban recovery.

First, existing research has largely addressed infrastructure monitoring, system performance, damage assessment, or individual operational tasks, whereas post-disaster recovery involves interactions among infrastructure conditions, environmental quality, resource constraints, and secondary risks[7–10,14–17]. Recent AI-enabled digital twin studies have further strengthened predictive and analytical capabilities, but these applications remain primarily oriented toward specific assets or operational systems[22–24]. A broader framework is therefore needed to connect these capabilities with urban-scale recovery planning.

Second, existing digital twin applications generally emphasize monitoring, simulation, or optimization of individual systems. They provide less explicit support for coordinating environmental conditions, chemical risks, resource availability, and competing recovery priorities within a common decision process. This limitation becomes particularly important when recovery strategies involve trade-offs between rapid restoration, environmental protection, and long-term resilience[1–6].

Third, environmental and chemical risks are often treated as separate assessment outputs rather than as dynamic variables that directly influence recovery decisions. Post-disaster chemical contamination may change over time as a result of pollutant release, migration, attenuation, reconstruction activities, and intervention. A recovery framework should therefore be capable of updating environmental-risk information and incorporating it into subsequent strategy evaluation.

Fourth, sustainability and resilience are increasingly recognized as complementary objectives in urban development and disaster management, yet their integration with digital twin-based recovery remains limited. Existing smart-city research emphasizes the importance of digital infrastructure, data integration, and adaptive urban management[11–13], but these capabilities have not been sufficiently connected with environmental-risk-aware recovery and sustainable resource allocation.

These gaps indicate the need for an integrated framework that can continuously update post-disaster urban conditions, evaluate environmental and chemical risks, coordinate constrained recovery resources, and support adaptive recovery decisions. The proposed DT-SRUR framework is designed to address this need through a closed-loop process linking data acquisition, environmental and risk assessment, digital twin state updating, recovery strategy evaluation, resource allocation, recovery action, and monitoring feedback.

1.3.Research objectives

To address the identified research gaps, this study proposes a Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR). The framework integrates digital twin technology with environmental quality assessment, chemical-risk prediction, sustainable resource management, and intelligent decision support to support adaptive recovery under changing disaster conditions.

Specifically, this study aims to:

(1)Develop an integrated digital twin framework for sustainable and resilient post-disaster urban recovery.

(2)Establish an environmental assessment mechanism that combines environmental quality assessment and chemical-risk analysis to support dynamic recovery planning.

(3)Design a sustainable resource management mechanism for coordinating recovery activities under constrained resources and competing recovery objectives.

(4)Construct an intelligent decision-support architecture that connects updated environmental, infrastructure, risk, and resource conditions with adaptive recovery decisions.

1.4.Research contributions

This study makes three primary contributions.

First, it proposes an integrated digital twin framework that connects environmental quality assessment, chemical-risk prediction, sustainable resource management, and intelligent decision support within a unified architecture for post-disaster urban recovery. The framework extends the application of digital twins from infrastructure-oriented monitoring and operational management toward environmental and recovery governance.

Second, the study introduces the Chemical Risk-Aware Digital Twin Environmental Risk Prediction Module (CR-DT-ERP). The module connects chemical-related environmental risk with digital twin state updating and recovery strategy evaluation, allowing chemical-risk information to influence subsequent recovery actions rather than being treated solely as a monitoring indicator.

Third, the study demonstrates the operation of the framework through a controlled synthetic post-earthquake simulation. Three recovery strategies—rapid restoration-oriented recovery, sustainability-oriented recovery, and digital twin-based adaptive recovery—are evaluated under common initial conditions and resource constraints. The comparison illustrates the trade-offs among recovery effectiveness, environmental performance, resilience, chemical risk, and resource consumption.

2.Literature review

2.1.Urban resilience and sustainable post-disaster recovery

Urban resilience has become an important concept for addressing increasing disaster risks and sustainability challenges in rapidly urbanizing environments. Contemporary resilience research has moved beyond resistance and rapid restoration toward flexibility, adaptation, learning, and long-term transformation of urban systems[1,2].

A resilience-oriented perspective also requires consideration of the relationships among physical infrastructure, environmental systems, social conditions, and institutional arrangements. Quantitative studies of seismic resilience have demonstrated the importance of robustness, rapidity, redundancy, and resourcefulness in determining community recovery performance[3]. Research on urban infrastructure resilience has similarly emphasized that recovery depends on interactions among infrastructure components rather than on the performance of individual assets alone[4].

The assessment of resilience has also increasingly incorporated broader social, economic, and environmental dimensions. Disaster resilience indicators have been developed to evaluate baseline community conditions and identify factors that influence recovery capacity[5]. At the same time, the increasing recognition of compound and cascading disasters has demonstrated that contemporary disasters may propagate across interconnected systems and generate multiple interacting risks[6]. Such characteristics make isolated or static recovery planning increasingly inadequate.

The governance dimension of resilience is also important. Urban resilience cannot be evaluated only according to whether a system returns to its previous state; it also involves questions concerning who benefits from recovery, what is being protected, when resilience is assessed, and how recovery priorities are established[2]. Sustainable post-disaster recovery therefore requires coordination among environmenta -l conditions, infrastructure functionality, resource availability, social needs, and governance decisions.

Despite these developments, many conventional recovery approaches still depend on fragmented information and periodic assessments. Such approaches can make it difficult to continuously identify changing environmental conditions, assess secondary risks, and adjust recovery priorities during the recovery process. This limitation provides a basis for considering digital technologies capable of supporting continuous state assessment and adaptive decision-making.

2.2.Digital twin technology and smart urban governance

Digital Twin technology has developed from engineering and manufacturing applications into a broader approach for representing and managing complex physical systems. In urban contexts, digital twins can provide dynamic digital representations of cities and support analysis and decision-making through continuous interaction between physical and virtual environments[7].

The technological foundation of digital twins involves the integration of sensing, data communication, modeling, simulation, analytics, and computational decision support. Reviews of digital twin technologies have highlighted their potential for monitoring, prediction, optimization, and lifecycle management, while also identifying challenges related to interoperability, data integration, modeling, and implementation[8,9]. From a modeling perspective, digital twins are particularly valuable when data and analytical models are connected rather than when digital representations are used only for visualization[10]. Systematic reviews have likewise identified continuous data exchange, simulation, and lifecycle-oriented analytical capabilities as important characteristics of digital twin systems[11].

Digital technologies have also become increasingly important in smart urban governance. Smart-city research has emphasized the role of digital innovation, information infrastructure, and technological integration in improving urban sustainability and governance[12]. The development of big-data-based urban analytics has further enabled cities to analyze complex urban processes using increasingly continuous information flows[13]. The concept of the real-time city similarly highlights how continuous data generation can support more adaptive forms of urban management[14].

The governance implications of digital technologies are particularly relevant to post-disaster recovery. A digital twin can potentially provide a shared analytical environment in which infrastructure conditions, environmental observations, resource availability, and recovery progress are continuously represented. However, many existing urban digital twin applications remain focused on operational monitoring and individual system management. Their use as integrated platforms for environmental-risk-aware and sustainability-oriented post-disaster recovery remains comparatively underdeveloped.

2.3.Digital twin applications in disaster recovery and research gaps

Digital twin research has demonstrated substantial potential for monitoring, prediction, optimization, and lifecycle management. In manufacturing and cyber-physical production systems, digital twins have been applied to support system monitoring and operational improvement[15]. Digital twin approaches have also been connected with big-data technologies to support complex-system analysis and smart manufacturing[16]. Predictive health management provides another important application area, where continuously updated system information is used to anticipate equipment conditions and support maintenance decisions[17]. Earlier research has similarly examined the role of digital twins in cyber-physical production systems and real-time system management[18].

Recent AI-oriented studies further illustrate the development of intelligent digital twin applications. Multimodal sensor data fusion has been used to support intelligent health assessment, while explainable machine learning has been applied to predictive decision-making and customer behavior analysis[22,23]. Digital twin architectures combined with explainable machine learning have also been explored for predictive maintenance of complex electromechanical systems[24]. These studies demonstrate that digital twins can increasingly incorporate AI-based analytical capabilities rather than functioning solely as digital representations.

However, the requirements of post-disaster urban recovery differ from those of individual asset monitoring or industrial predictive maintenance. Recovery decisions must account for multiple interconnected dimensions, including infrastructure functionality, environmental quality, chemical risk, resource constraints, and resilience objectives. This difference reveals several limitations in current digital twin applications.

First, existing digital twin research remains strongly oriented toward infrastructure, manufacturing, asset management, and operational optimization[7-11,15-18,22-24]. The integration of these capabilities into a broader post-disaster urban recovery process remains limited.

Second, existing disaster-related approaches often emphasize damage assessment, resilience evaluation, or emergency response, whereas recovery is a longer-term process in which environmental conditions, resource availability, and secondary risks may evolve continuously[3-6]. A recovery-oriented digital twin therefore needs to support not only observation but also state updating, scenario evaluation, and adaptive intervention.

Third, environmental and chemical risks remain insufficiently connected to digital twin-based recovery decision-making. Existing digital twin research demonstrates strong capabilities in data integration and prediction[8-11], but the dynamic evolution of chemical contamination and its implications for recovery strategy selection have received comparatively limited attention.

Fourth, sustainability and resilience require trade-offs rather than optimization of a single recovery indicator. Rapid infrastructure restoration may improve short-term recovery effectiveness but increase environmental pressures, whereas environmentally conservative strategies may reduce immediate recovery speed. An adaptive framework should therefore allow these competing objectives to be evaluated under common resource constraints.

Accordingly, the present study develops DT-SRUR as a closed-loop recovery framework that integrates:

(1)continuous urban and environmental condition assessment;
(2)dynamic chemical-risk prediction;
(3)digital twin state synchronization;
(4)recovery strategy evaluation;
(5)sustainable resource allocation;
(6)feedback-based adaptive recovery decisions.

The framework is subsequently demonstrated through a synthetic post-earthquake scenario in Section 4, where rapid restoration, sustainability-oriented, and digital twin-based adaptive recovery strategies are compared under the same initial conditions and a common resource constraint.

3.Conceptual framework and methodology

3.1.Framework development and theoretical foundation

Post-disaster urban recovery is a complex adaptive process involving interactions among physical infrastructure, environmental systems, resource networks, social needs, and governance mechanisms. Unlike conventional reconstruction, which primarily focuses on restoring damaged facilities and urban functions, sustainable recovery requires simultaneous consideration of environmental conditions, emerging risks, resource constraints, and long-term resilience.

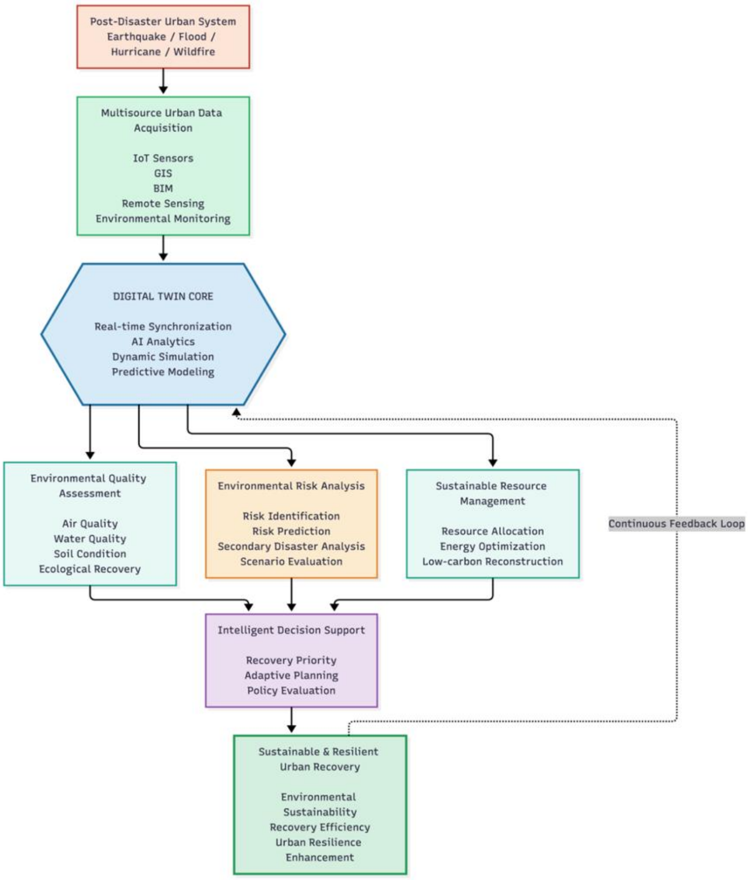

Fig 1. Integrated digital twin framework for sustainable and resilient post-disaster urban recovery

Conventional recovery processes often depend on fragmented information, periodic assessment, and relatively fixed planning decisions. Such approaches may be effective for initial emergency response but are less suitable when environmental conditions, infrastructure functionality, resource availability, and recovery risks change continuously. Therefore, an effective recovery framework should establish a connection between continuously updated urban information and adaptive recovery decisions.

Based on this requirement, this study develops a Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR). The framework uses digital twin technology as the coordination layer between the physical urban system and its virtual representation. Its purpose is not to introduce digital twin technology as an independent monitoring platform, but to use continuously updated system information to support risk-aware recovery evaluation and adaptive resource decisions.

The framework is conceptually grounded in four complementary perspectives. Urban resilience theory provides the basis for treating recovery as a process of restoring essential functions while improving the capacity to withstand future disturbances. Sustainable development theory establishes the need to balance recovery efficiency, environmental protection, resource use, and long-term urban development. Environmental assessment and risk analysis provide the basis for identifying changing environmental conditions and potential secondary risks during recovery. Digital twin theory provides the technological mechanism for synchronizing physical-system observations with virtual models and evaluating alternative recovery conditions.

Accordingly, DT-SRUR represents post-disaster recovery as a closed-loop process:

Multisource Data → Environmental and Risk Assessment → Digital Twin State Update → Recovery Strategy Evaluation → Resource Allocation → Recovery Action → Feedback

The distinctive contribution of DT-SRUR does not lie in the individual use of digital twins, environmental assessment, or resource optimization, which have been investigated in previous studies. Instead, its contribution lies in connecting these functions through a chemical-risk-aware adaptive recovery loop. First, the framework incorporates chemical-risk perception and prediction into the digital twin rather than treating environmental risk as an independent monitoring output. Second, the resulting chemical-risk information is linked directly to recovery strategy evaluation and resource allocation, allowing environmental risk to influence recovery decisions. Third, the framework adopts a feedback mechanism through which updated infrastructure, environmental, risk, and resource states can modify subsequent recovery actions. Therefore, DT-SRUR is designed as a risk-aware adaptive recovery coordination framework, rather than simply another digital twin architecture for post-disaster monitoring.

The detailed functional components and computational relationships of the framework are presented in Section 3.2, while their operation under a specific post-earthquake scenario is examined through the scenario-based computational demonstration in Section 4.

3.2.Architecture of the digital twin-based recovery framework

The proposed DT-SRUR framework consists of seven interconnected functional components: urban data acquisition, environmental quality assessment, chemical risk-aware digital twin environmental risk prediction, risk analysis, digital twin modeling, sustainable resource management, and intelligent decision support. Together, these components establish an integrated architecture for monitoring, analyzing, and optimizing post-disaster urban recovery processes.

3.2.1.Urban data acquisition and integration

The first component provides the data foundation for digital twin construction. Post-disaster urban recovery involves changing interactions among environmental conditions, infrastructure, population, and resource availability, making timely and reliable data essential for recovery assessment. The proposed framework integrates heterogeneous sources, including IoT sensors, GIS, remote sensing, environmental monitoring systems, infrastructure databases, and urban management platforms. These data provide information on environmental conditions, infrastructure status, population distribution, resource availability, and recovery conditions. After integration and preprocessing, the data are converted into a unified urban information environment that supports environmental assessment and digital twin state updating.

3.2.2.Environmental quality assessment mechanism

Environmental quality assessment provides an important basis for sustainable post-disaster recovery. Disasters and subsequent reconstruction activities may affect air, water, soil, ecological conditions, and chemical risk. The proposed framework integrates environmental information into the digital twin to continuously track these changes during recovery. Combined with infrastructure and resource conditions, the assessment results support the identification of priority intervention areas and the evaluation of environmental implications under different recovery strategies. This ensures that recovery decisions consider not only physical restoration but also environmental protection and long-term sustainability.

3.2.3.Chemical risk-aware digital twin environmental risk prediction module

In this study, chemical risk is considered as an important component of post-disaster environmental risks, particularly arising from hazardous material leakage, industrial facility damage, infrastructure disruption, and reconstruction-related pollution.

Post-disaster urban environments often involve complex and dynamic chemical-related risks, including pollutant release, contaminant migration, environmental accumulation, and potential secondary pollution during recovery processes. Existing digital twin applications in disaster management have predominantly focused on infrastructure monitoring, damage assessment, and operational optimization, while relatively limited attention has been devoted to the dynamic evolution of environmental chemical risks and their integration into predictive recovery decision-making.

To address this limitation, this study proposes a Chemical Risk-Aware Digital Twin Environmental Risk Prediction Module (CR-DT-ERP) within the DT-SRUR framework. The proposed module integrates environmental monitoring data, chemical risk indicators, contaminant migration analysis, and digital twin simulation to enhance the capability of digital twin systems in identifying, predicting, and managing post-disaster environmental risks.

Unlike conventional digital twin applications that mainly provide real-time monitoring and visualization, the proposed module extends digital twin capabilities toward risk-aware prediction and adaptive environmental recovery support. By incorporating chemical-related risk factors into the digital twin environment, the framework enables dynamic assessment of pollution evolution, evaluation of recovery strategies, and optimization of sustainable urban recovery decisions.

The module consists of three key mechanisms.

(1) Chemical mechanism-embedded environmental modeling

The proposed module integrates chemical mechanisms into the digital twin architecture, enabling the virtual urban environment to represent not only current pollution conditions but also the dynamic evolution of chemical risks.

The model can be expressed as:

$$DT_{chem}=D_p+C_m+D_d \tag{1}$$

where: DT_{chem} represents the chemistry-informed digital twin model; D_{p} represents physical urban environmental data; C_{m} represents chemical mechanism models; D_{d} represents dynamic monitoring data.

Unlike conventional data-driven digital twins, this approach combines real-time environmental information with chemical knowledge, improving the capability of digital twins to understand and predict post-disaster environmental changes.

(2) Dynamic chemical risk prediction mechanism

Post-disaster chemical pollution is a continuous process involving pollutant release, migration, transformation, and accumulation. Therefore, the proposed framework incorporates contaminant lifecycle modeling to predict future environmental risks.

The pollutant evolution process is represented as:

$$C_t+1=f(C_t,M_t,E_t,R_t) \quad (2)$$

where: C_t represents current contaminant concentration; M_t represents pollutant migration characteristics; E_t represents environmental conditions; R_t represents recovery intervention effects.

Through continuous synchronization between physical environments and virtual models, the digital twin can predict future pollution hotspots, risk evolution trends, and environmental impacts under different recovery strategies.

(3) Chemical risk-oriented recovery optimization

Different recovery strategies may generate different environmental consequences. For example, rapid reconstructi -on may improve recovery efficiency but increase pollution risks, while sustainable reconstruction may reduce environmental impacts but require additional coordination.

Therefore, this study incorporates chemical risk into the recovery optimization objective:

$$maxF_1=\alpha R+\beta S+\gamma Res-\lambda CR \quad (3)$$

where: R represents recovery effectiveness; S represents sustainability performance; Res represents resilience improvement; CR represents chemical risk.

By simulating alternative recovery scenarios, the digital twin framework supports decision-makers in selecting recovery strategies that balance restoration efficiency, environmental safety, and long-term urban resilience.

The major innovation of this module is that it extends digital twin technology from a data representation and monitoring tool toward a chemistry-informed predictive environmental intelligence system. By integrating chemical mechanisms with dynamic simulation capabilities, the proposed framework enables early identification of post-disaster environmental risks, optimization of recovery strategies, and improvement of sustainable urban resilience.

3.2.4.Risk analysis mechanism

The risk analysis component aims to identify, evaluate, and manage potential uncertainties throughout the recovery process. Post-disaster environments often involve multiple interconnected risks, including environmental risks, infrastructure risks, resource supply risks, and secondary disaster risks.

Within the proposed framework, risk analysis is conducted through:

(1)identification of critical risk factors;

(2)assessment of potential impacts;

(3)prioritization of recovery requirements;

(4)simulation of risk evolution under different scenarios.

By combining environmental information, infrastructure conditions, and resource constraints, the framework enables a comprehensive understanding of recovery-related risks.

Unlike traditional risk assessment approaches based on static evaluation, the proposed digital twin-based mechanism supports dynamic risk monitoring and adaptive response strategies.

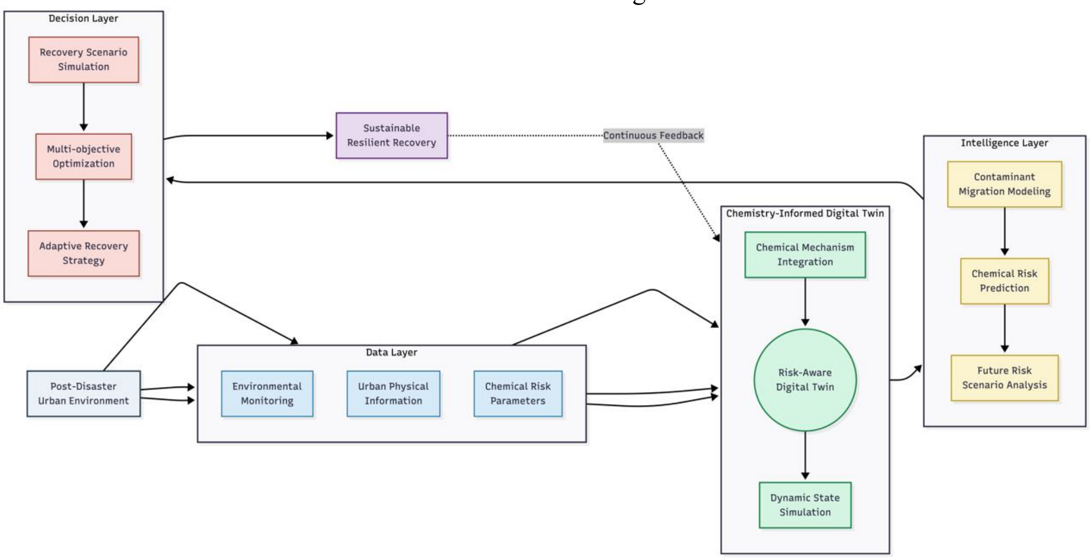

Fig 2. Conceptual framework of the chemical risk-aware digital twin environmental risk prediction module (CR-DT-ERP)

Table 1. Comparison between conventional digital twin applications and the proposed chemistry-informed digital twin module

Dimension	Conventional Digital Twin Applications	Proposed Chemistry-Informed Digital Twin Module
Data sources	Sensor data, GIS, infrastructure information	Environmental data, chemical mechanisms, and dynamic monitoring data
Core capability	Status monitoring and visualization	Monitoring, prediction, and risk-based optimization
Environmental analysis	Evaluation based on current conditions	Prediction based on chemical migration and transformation processes
Risk management	Reactive response after risk occurrence	Proactive prediction and early intervention
Decision support	Information visualization and analysis	Scenario simulation and recovery strategy optimization
Main objective	Improving operational efficiency	Supporting sustainable and resilient environmental recovery

3.2.5.Digital twin modeling mechanism

The digital twin modeling component establishes a dynamic virtual representation of the post-disaster urban system by integrating environmental, spatial, infrastructure, recovery, and resource information. Unlike a conventional digital model, the proposed digital twin is continuously updated as new observations become available, allowing the virtual state to reflect changing post-disaster conditions.

Based on the updated system state, the digital twin supports the simulation and comparison of alternative recovery strategies before their implementation. This provides a common analytical environment for linking environmental conditions, infrastructure recovery, resource constraints, and risk information, thereby supporting more adaptive recovery decisions.

3.2.6.Sustainable resource management mechanism

Post-disaster recovery is constrained by limited financial resources, materials, labor capacity, energy availability, and environmental carrying capacity. Therefore, sustainable resource management is essential for achieving efficient and resilient reconstruction.

The proposed framework treats resource management as a multi-objective coordination problem considering:

- recovery efficiency;
- environmental sustainability;
- resource availability;
- resilience enhancement;
- long-term urban development objectives.

The optimization objective can be expressed as:

$$Maximize\ F_2=\alpha R+\beta S+\gamma Res-\lambda C \quad (4)$$

Where: R represents recovery efficiency; S represents sustainability performance; Res represents resilience enhancement; C represents recovery cost; α, β, γ, λ represent weighting coefficients.

This mechanism enables decision-makers to identify recovery strategies that achieve a balance between immediate reconstruction needs and long-term sustainability objectives.

3.2.7.Intelligent decision-support mechanism

The intelligent decision-support mechanism converts the updated digital twin state into recovery actions. It considers infrastructure conditions, environmental risks, resource availability, and recovery priorities to support the selection and adjustment of recovery strategies.

Within the digital twin environment, alternative recovery strategies can be evaluated before implementation, allowing decision-makers to compare their effects on recovery performance, environmental conditions, resource use, and resilience. As new monitoring information becomes available, the assessment can be updated and recovery priorities or resource allocation can be adjusted accordingly.

This mechanism therefore provides the decision layer of DT-SRUR, linking environmental and infrastructure assessment with strategy evaluation and adaptive recovery planning.

3.3.Research methodology and framework evaluation

This study adopts a conceptual framework development methodology combined with scenario-based evaluation. The research process consists of three stages.

First, theoretical analysis and literature synthesis are conducted to identify limitations in existing digital twin applications and post-disaster recovery approaches.

Second, an integrated framework is developed by combining digital twin technology with environmental assessment, risk analysis, sustainable resource management, and resilience governance principles.

Third, a scenario-based evaluation approach is applied to demonstrate the practical applicability of the proposed framework in post-disaster urban recovery contexts.

The framework is evaluated from three perspectives:

(1) Environmental assessment capability

Whether the framework can effectively integrate environmental information and support continuous evaluation of post-disaster environmental conditions.

(2) Decision-support capability

Whether the framework can support adaptive recovery planning, risk-informed decisions, and sustainable resource allocation.

(3) Sustainability and resilience contribution

Whether the framework can enhance long-term urban adaptability, environmental sustainability, and recovery effectiveness.

Through this methodology, the study provides a conceptual foundation for integrating digital twin technology into sustainable and resilient urban recovery governance.

4.Post-earthquake scenario simulation and computational demonstration

4.1.Post-earthquake scenario and synthetic simulation inputs

To demonstrate how the proposed Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR) can operate under a specific disaster context, this study develops a controlled hypothetical post-earthquake urban recovery scenario. The purpose of this scenario is to provide a structured computational environment for examining the interaction among infrastructure recovery, environmental conditions, chemical risk, resilience, and resource constraints. It is not intended to reproduce a specific historical earthquake or represent a particular real-world city.

A medium-sized urban area is assumed to experience a severe earthquake that damages residential areas, transportation networks, water and energy facilities, and public service infrastructure. In addition to direct physical damage, the earthquake generates secondary environmental pressures during

the recovery period. Particular attention is given to a damaged industrial or hazardous-material storage facility, where structural failure is assumed to create a potential chemical contamination source. The resulting chemical risk is treated as a dynamic condition that may change with environmental attenuation, recovery intervention, and updated monitoring information.

The simulation covers 30 days after the earthquake, with the digital twin state updated at seven-day intervals. Four categories of information are considered: infrastructure functionality, environmental quality, chemical-risk conditions, and recovery resources. The same initial conditions and total resource capacity are used for all three recovery strategies so that their differences arise from the recovery decision rules rather than from different initial settings.

Because site-specific post-earthquake monitoring data are not available for this study, synthetic scenario inputs are used. These inputs are intended solely for controlled computational demonstration and should not be interpreted as measurements from an actual post-earthquake event.

The computational process follows the framework developed in Section 3:

Initial State → Assessment → Digital Twin Update → Recovery Strategy Evaluation → Resource Allocation → Recovery Action → Monitoring Feedback → State Update

Accordingly, this section focuses on the implementation of the framework under a specific earthquake scenario rather than redefining its conceptual components.

4.2.Recovery strategies and computational procedure

Three recovery strategies are considered.

Scenario A: Rapid Restoration-Oriented Recovery. This strategy prioritizes the rapid restoration of critical urban functions. Available resources are mainly directed toward infrastructure repair, transportation restoration, and water and energy services. Environmental and chemical-risk considerations are incorporated but receive relatively lower priority during the early recovery stage.

Table 2. Main parameters of the synthetic post-earthquake scenario

Parameter	Symbol	Baseline value	Description
Simulation period	(T)	30 days	Duration of the post-earthquake simulation
Initial infrastructure functionality	(F_0)	0.40	Normalized functionality immediately after the earthquake
Initial environmental quality	(E_0)	0.45	Normalized environmental condition immediately after the earthquake
Initial chemical concentration	(C_0)	1.00	Normalized initial chemical-risk level
Available recovery resources	(B)	100 units	Total normalized recovery-resource capacity
Digital twin update interval	(Δt)	7 days	Interval for state synchronization and recovery adjustment

Note: All numerical values are synthetic scenario inputs used for controlled computational demonstration and do not represent measurements from a specific post-earthquake city.

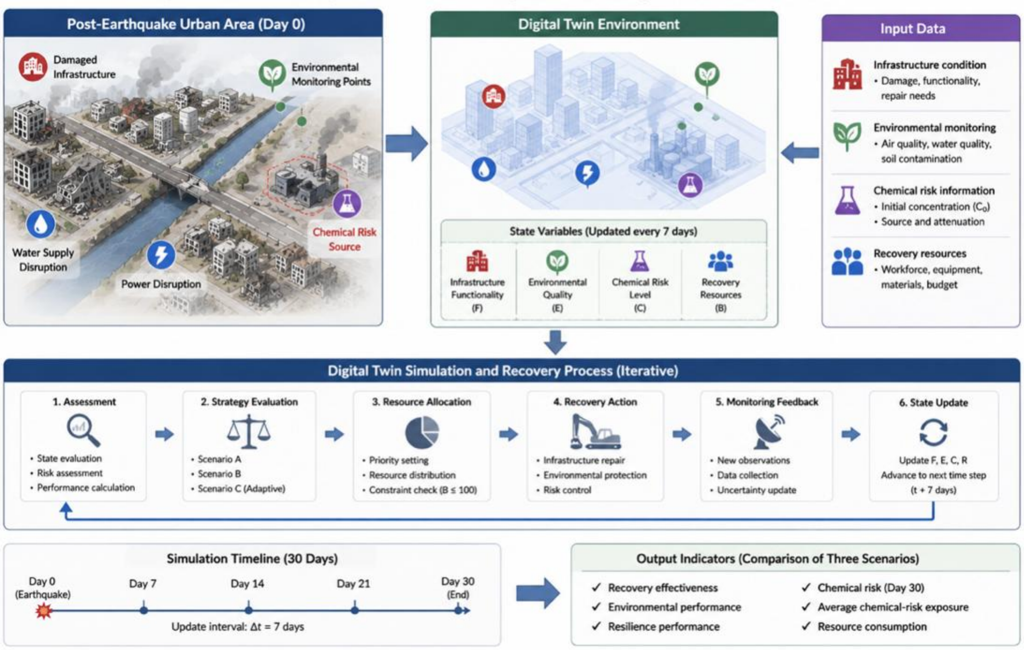

Fig 3. Post-earthquake scenario configuration and digital twin simulation process

Scenario B: Sustainability-Oriented Recovery. This strategy places greater emphasis on environmental protection and

sustainable reconstruction. Resources are relatively more strongly directed toward pollution prevention, environmentally responsible reconstruction, waste reduction, and ecological restoration. Consequently, environmental performance is prioritized even when this may reduce the rate of short-term functional recovery.

Scenario C: Digital Twin-Based Adaptive Recovery. This strategy represents the proposed DT-SRUR approach. Instead of maintaining a fixed recovery priority throughout the simulation, resource allocation is adjusted according to the evolving digital twin state. Infrastructure functionality, environmental conditions, chemical risk, resilience requirements, and remaining resources are considered together when determining subsequent recovery actions.

All three strategies start from the same initial conditions and operate under the same resource capacity:

$$F_0=0.40,\ E_0=0.45,\ C_0=1.00 \tag{5}$$

$$B=100 \tag{6}$$

At each seven-day update point, the current state is assessed and the next recovery action is determined. The computational transition can be represented as:

$$S_t \rightarrow Assessment \rightarrow Decision \rightarrow Action \rightarrow S_{t+1} \quad (7)$$

where S_t denotes the current state of the digital twin.

For Scenario A and Scenario B, the principal recovery priorities remain relatively stable throughout the simulation. For Scenario C, the allocation is adjusted according to changes in infrastructure functionality, environmental quality, chemical risk, and available resources. This provides a computational representation of the adaptive feedback mechanism described in Section 3.

4.3.Earthquake-specific chemical-risk simulation

A dedicated computational simulation is conducted to demonstrate the operation of the Chemical Risk-Aware Digital Twin Environmental Risk Prediction Module (CR-DT-ERP) under the post-earthquake scenario. This component is particularly relevant because damage to industrial facilities or hazardous-material storage systems may generate environmental risks that evolve during recovery.

Following the assumed earthquake damage, the initial normalized chemical concentration is set to:

$$C_0 = 1.00 \quad (8)$$

The subsequent evolution of chemical concentration is represented using the following simplified scenario-level relationship:

$$C_{t+1} = C_i e^{-k_t} \quad (9)$$

where C_t represents the normalized chemical concentration at time *t*, and k_t represents the combined effect of environmental attenuation and recovery intervention.

This formulation is used as a computational representation of chemical-risk evolution rather than as a site-specific physicochemical transport model. It does not attempt to reproduce the complete dispersion, migration, reaction, or transformation processes of a particular chemical. In an actual deployment, the parameter k_t could be replaced or calibrated using contaminant-specific transport models and real environmental monitoring observations.

The three recovery strategies apply different levels and timing of chemical-risk intervention. Scenario A gives greater priority to rapid infrastructure restoration. Scenario B gives stronger priority to environmental protection. Scenario C adjusts chemical-risk intervention according to the updated digital twin state.

Chemical risk is evaluated throughout the 30-day simulation, with state updates at Days 0, 7, 14, 21, and 30. In addition to the chemical-risk level at Day 30, average chemical-risk exposure is considered to capture the overall risk condition during the recovery period.

The simulation therefore demonstrates how chemical-risk information can be incorporated into the recovery decision process rather than being treated solely as a separate environmental monitoring indicator.

Table 3. Chemical-risk simulation configuration

Variable	Baseline setting	Description
Initial chemical concentration	1.00	Normalized post-earthquake contamination level
Simulation horizon	30 days	Period of chemical-risk evolution
Digital twin update interval	7 days	Frequency of state synchronization
Chemical-risk intervention	Strategy-dependent	Determines the intervention effect
Risk observation points	Days 0, 7, 14, 21, 30	Used to evaluate risk evolution

Table 4. Quantitative comparison of the three recovery strategies

Indicator	Scenario A: Rapid Restoration	Scenario B: Sustainability-Oriented	Scenario C: DT-Based Adaptive
Recovery effectiveness	0.706	0.682	0.690
Environmental performance	0.477	0.492	0.489
Resilience performance	0.445	0.432	0.447
Chemical risk at Day 30	0.757	0.736	0.729
Average chemical-risk exposure	0.845	0.833	0.825
Resource consumption (units)	88	81	83

Note: The values are generated from the synthetic post-earthquake computational simulation described in Sections 4.1–4.3. All three strategies use the same initial conditions and total resource capacity. The results are intended to demonstrate comparative framework behavior rather than represent measurements from a specific post-earthquake city.

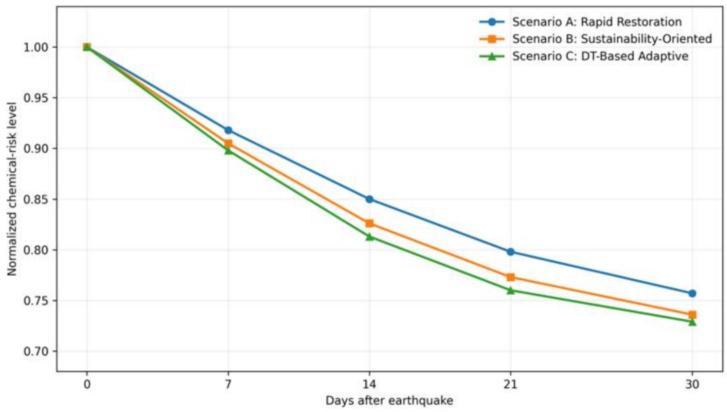

Fig 4. Simulated chemical-risk evolution under the three recovery strategies

4.4. Quantitative comparison of the three recovery strategies

The computational outputs are compared using recovery effectiveness, environmental performance, resilience performance, chemical risk, and resource consumption. The indicators are normalized where appropriate to provide a common basis for comparison.

The results demonstrate distinct trade-offs among the three recovery strategies. Scenario A achieves the highest recovery effectiveness, with a value of 0.706. This result is consistent with its emphasis on rapid restoration of critical urban functions. However, this strategy produces the lowest environmental performance (0.477) and a relatively lower resilience performance (0.445). It also produces the highest chemical risk at Day 30 (0.757) and the highest average chemical-risk exposure (0.845). The results therefore indicate a clear trade-off between rapid functional restoration and environmental-risk control.

Scenario B achieves the highest environmental performance, with a value of 0.492. It also reduces the Day-30 chemical risk to 0.736 and the average chemical-risk exposure to 0.833. However, its recovery effectiveness is 0.682, the lowest among the three strategies. This pattern is consistent with a strategy that assigns greater priority to environmental protection and sustainable reconstruction. Scenario B also has the lowest resource consumption, at 81 units, indicating relatively strong resource efficiency within the simulated conditions.

Scenario C does not produce the highest value for every individual indicator. Its recovery effectiveness is 0.690, slightly below Scenario A but above Scenario B. Its environmental performance is 0.489, very close to the highest value obtained by Scenario B. However, Scenario C achieves the highest resilience performance (0.447), the lowest Day-30 chemical risk (0.729), and the lowest average chemical-risk exposure (0.825). Its resource consumption is 83 units, which lies between Scenario A and Scenario B.

This pattern is important for interpreting the contribution of the proposed adaptive strategy. The simulation does not suggest that DT-SRUR universally dominates alternative recovery strategies. Instead, Scenario C demonstrates a more balanced performance across competing objectives. It sacrifices a small amount of recovery effectiveness relative to the rapid restoration strategy while achieving lower chemical risk and higher resilience. At the same time, it approaches the environmental performance of the sustainability-oriented strategy without adopting exactly the same fixed recovery priorities.

The chemical-risk results provide a specific computational demonstration of the proposed CR-DT-ERP component. The simulated Day-30 chemical-risk level decreases from 0.757 under Scenario A to 0.736 under Scenario B and 0.729 under Scenario C. Similarly, average chemical-risk exposure decreases from 0.845 to 0.833 and 0.825, respectively. These results indicate that incorporating evolving chemical-risk information into recovery decisions can alter the simulated recovery trajectory and improve risk-oriented decision support.

The resource results further illustrate the trade-offs among the strategies. Scenario A consumes 88 units, Scenario B consumes 81 units, and Scenario C consumes 83 units from the common 100-unit resource capacity. Therefore, the improved resilience and chemical-risk performance of Scenario C is not based on an assumption of unlimited resources. Instead, the adaptive strategy operates under the same resource constraint while adjusting priorities according to the evolving simulated state.

Overall, the computational results suggest that the main value of Scenario C lies in adaptive coordination among competing recovery objectives, rather than maximizing a single indicator. This finding is consistent with the central design principle of DT-SRUR: recovery decisions should be updated as environmental, risk, infrastructure, and resource conditions change.

4.5. Computational interpretation, robustness, and limitations

The scenario simulation provides a computational demonstration of the closed-loop operation proposed in Section 3. During the simulated recovery period, monitoring information is incorporated into the digital twin, the current state is reassessed, and subsequent recovery priorities are adjusted. The process can be summarized as:

Monitoring → State Update → Risk Reassessment → Resource Adjustment → Recovery Action → New Monitoring

This mechanism distinguishes Scenario C from the two fixed-priority strategies. Scenario A maintains its emphasis on rapid restoration, whereas Scenario B maintains its emphasis on sustainability. Scenario C allows the relative importance of recovery requirements to change as the simulated urban state evolves.

The chemical-risk simulation provides a focused demonstration of how the proposed framework can incorporate a disaster-specific environmental risk into recovery decision-making. Rather than treating chemical risk as a static indicator, the simulation represents it as an evolving condition that can affect subsequent recovery priorities. This provides a concrete computational illustration of the chemistry-informed component introduced in Section 3.

The results should nevertheless be interpreted conservatively. The present study does not claim to provide empirical evidence from a real earthquake. The numerical values are generated from synthetic scenario inputs and simplified computational relationships. Their primary purpose is to demonstrate the internal operation of the framework and provide a controlled comparison of alternative recovery strategies.

The scenario also has several limitations. First, site-specific post-earthquake monitoring data were unavailable, preventing direct calibration of the model. Second, the chemical-risk relationship is a simplified representation and does not reproduce the full physicochemical behavior of a particular contaminant. Third, real urban recovery involves additional factors, including detailed infrastructure interdependencies, population behavior, institutional coordination, transportation disruption, and spatially heterogeneous environmental processes.

Therefore, the results should not be interpreted as predictions for a particular city or as evidence that DT-SRUR will outperform alternative strategies under all real-world conditions. Instead, they demonstrate that the proposed framework provides a structured computational environment in which alternative recovery strategies can be evaluated under common initial conditions and resource constraints, while simultaneously considering recovery effectiveness, environmental performance, resilience, and chemical risk.

Future research should incorporate real post-earthquake monitoring observations, infrastructure damage records, site-specific contaminant transport models, and actual recovery-resource data. These data would allow the framework to be calibrated and subsequently evaluated under real-world conditions. Such work would constitute a further stage of external assessment beyond the present synthetic scenario-based computational demonstration.

5.Discussion

5.1.Contribution to digital twin-enabled urban recovery

The results support the use of digital twins as a coordination mechanism for post-disaster recovery rather than only as tools for monitoring or visualization. Existing digital twin research has mainly emphasized data integration, system representation, simulation, and operational decision support[9-13]. The proposed DT-SRUR framework extends this role to post-disaster recovery by connecting urban state information with environmental assessment, risk evaluation, resource allocation, and recovery actions.

The scenario comparison in Section 4 shows that the value of the proposed approach is not simply to maximize one recovery indicator. The rapid restoration strategy provides stronger short-term functional recovery, while the sustainability-oriented strategy places greater emphasis on environmental performance and resource use. The DT-based adaptive strategy provides a more balanced outcome by adjusting recovery priorities according to the changing simulated state. This is consistent with the broader understanding of urban resilience as an adaptive capacity rather than a simple return to pre-disaster conditions[1–4].

The main contribution is therefore the integration of these functions within a single recovery loop. Instead of treating infrastructure recovery, environmental risk, and resource management as separate tasks, DT-SRUR links them through continuous state updating and strategy adjustment. This provides a practical way to translate the concept of adaptive urban resilience into a digital decision-support process.

5.2.Environmental risk and adaptive recovery

Environmental risk is an important part of post-disaster recovery because disaster impacts may continue after the initial physical event. Conventional recovery planning can place greater emphasis on infrastructure restoration, while environmental changes and secondary risks may receive less attention. The proposed framework addresses this issue by incorporating environmental conditions and chemical-related risk into the digital twin state.

The computational demonstration in Section 4 provides a focused example of this mechanism. The chemical-risk component represents contamination as an evolving condition affected by environmental attenuation and recovery intervention. The purpose is not to reproduce the complete physicochemical behavior of a specific contaminant, but to demonstrate how changing environmental risk can be incorporated into recovery decisions.

The results show that the adaptive strategy can reduce simulated chemical-risk exposure while maintaining a recovery performance close to the rapid restoration strategy. This finding should be interpreted as evidence of the decision mechanism demonstrated by the scenario, rather than as empirical evidence of improved chemical-risk prediction. In this sense, the contribution of the chemical-risk module is its integration into the recovery decision loop rather than the development of a site-specific contaminant transport model.

5.3.Resource management and recovery trade-offs

Post-disaster recovery is normally subject to limited financial, material, energy, and labor resources. A recovery strategy that maximizes restoration speed may therefore impose additional environmental or resource costs. Conversely, a strategy that gives strong priority to environmental protection may slow the restoration of essential urban functions.

The results presented in Section 4 illustrate this trade-off under a common resource constraint. The three strategies produce different combinations of recovery effectiveness, environmental performance, resilience, chemical risk, and resource consumption. The DT-based strategy does not achieve the best value for every individual indicator, but instead adjusts priorities according to the evolving recovery state.

This result supports the central role of adaptive resource coordination in DT-SRUR. Rather than assigning fixed priorities throughout the recovery period, the framework allows resource decisions to respond to changes in infrastructure conditions, environmental quality, chemical risk, and remaining resources. Such an approach is more consistent with the dynamic and interconnected nature of urban recovery[1,2].

Table 5. Comparison of traditional recovery approaches, existing digital twin applications, and the proposed DT-SRUR framework

Dimension	Traditional Recovery Approaches	Existing Digital Twin Applications	Proposed DT-SRUR Framework
Information integration	Fragmented and delayed	Real-time monitoring	Integrated environmental and urban data
Environmental consideration	Limited	Mainly operational	Environmental assessment and risk analysis
Decision-making	Experience-based	Data-supported	Simulation-based adaptive support
Resource management	Static allocation	Limited optimization	Sustainable resource coordination
Recovery objective	Restoration-oriented	Efficiency-oriented	Sustainability and resilience-oriented

5.4.Practical implications

The proposed framework has several practical implications for post-disaster management. First, it provides a common digital environment for combining infrastructure, environmental, risk, and resource information, which can reduce fragmentation between different recovery activities. Second, the framework allows alternative recovery strategies to be evaluated before implementation, helping decision-makers examine potential trade-offs between rapid restoration and environmental protection. Third, the adaptive mechanism provides a basis for adjusting recovery priorities as new monitoring information becomes available.

The framework may therefore be useful for emergency management agencies, urban planners, infrastructure operators, and local governments. However, its practical value depends on the availability and quality of real-time data, reliable environmental models, and effective institutional coordination. Digital twin technology alone cannot resolve these organizational and data-related constraints[10–13].

5.5.Limitations and future research

The findings of this study should be interpreted within the scope of the scenario-based evaluation. The computational demonstration uses synthetic post-earthquake inputs and simplified assumptions to examine the operation and comparative behavior of the proposed framework. It therefore does not provide empirical validation for a specific city or disaster event. In addition, the chemical-risk component represents contaminant evolution at a simplified scenario level and does not reproduce the detailed transport, dispersion, reaction, or transformation processes of a specific chemical. The current framework also does not fully capture infrastructure interdependencies, population responses, or institutional coordination.

Future research should validate DT-SRUR using real disaster cases and monitoring data. Real infrastructure damage records, environmental observations, contaminant transport models, and recovery-resource data could be incorporated to improve model calibration and scenario realism. Further work could also introduce more detailed optimization and predictive methods to strengthen adaptive recovery planning while retaining the framework's focus on environmental risk, resource coordination, and urban resilience.

6.Conclusion

6.1.Main findings and contributions

This study developed a Digital Twin Framework for Sustainable and Resilient Post-Disaster Urban Recovery (DT-SRUR) to support adaptive recovery under changing environmental, risk, infrastructure, and resource conditions. The framework connects multisource urban information, environmental assessment, risk analysis, digital twin state updating, resource coordination, and recovery decision-making within a closed-loop process.

The scenario-based computational demonstration shows that different recovery strategies produce different trade-offs. Rapid restoration favors functional recovery, sustainability-oriented recovery places greater emphasis on environmental performance and resource use, while the proposed DT-based adaptive strategy provides a more balanced response across the considered objectives. The chemical-risk simulation further demonstrates how an evolving environmental risk can be incorporated into recovery decisions instead of being treated only as a separate monitoring indicator.

The contribution of DT-SRUR therefore lies primarily in adaptive coordination rather than single-objective optimization. By linking environmental risk, recovery performance, resilience, and resource constraints within the same decision process, the framework provides a structured approach for evaluating and adjusting post-disaster recovery strategies. It also extends the role of digital twins from system monitoring toward integrated recovery decision support[9–13].

6.2.Limitations and future directions

The findings should be interpreted within the scope of the synthetic scenario used in this study. The computational results are not intended to predict the performance of a particular city or disaster event, and the simplified chemical-risk model cannot replace contaminant-specific environmental modeling. Future research should validate DT-SRUR using real disaster cases and integrate real-time environmental observations, infrastructure damage data, and recovery-resource information. More detailed chemical transport models and advanced predictive methods could also be incorporated to improve the framework's external validity.

Overall, DT-SRUR provides a foundation for linking digital twin technology with environmental risk management and adaptive resource coordination in post-disaster urban recovery. Its further development will depend on empirical validation, improved data integration, and closer integration with real-world recovery governance.

References

[1] AHERN J. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape and Urban Planning, 2011, 100(4): 341-343.

[2] MEEROW S, NEWELL J P, STULTS M. Defining urban resilience: A review. Landscape and Urban Planning, 2016, 147: 38-49.

[3] BRUNEAU M, CHANG S E, EGUCHI R T, et al. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 2003, 19(4): 733-752.

[4] OUYANG M, DUEÑAS-OSORIO L, MIN X. A three-stage resilience analysis framework for urban infrastructure systems. Structural Safety, 2012, 36-37: 23-31.

[5] CUTTER S L, BURTON C G, EMRICH C T. Disaster resilience indicators for benchmarking baseline conditions. Journal of Homeland Security and Emergency Management, 2010, 7(1).

[6] CUTTER S L. Compound, cascading, or complex disasters: What's in a name? Environment: Science and Policy for Sustainable Development, 2018, 60(6): 16-25.

[7] MEEROW S, NEWELL J P. Urban resilience for whom, what, when, where, and why? Urban Geography, 2019, 40(3): 309-329.

[8] ZHANG X, SONG J, PENG J, et al. Landslides-oriented urban disaster resilience assessment: A case study in Shenzhen, China. Science of the Total Environment, 2019, 661: 95-106.

[9] BATTY M. Digital twins. Environment and Planning B: Urban Analytics and City Science, 2018, 45(5): 817-820.
[10] FULLER A, FAN Z, DAY C, et al. Digital twin: Enabling technologies, challenges and open research. IEEE Access, 2020, 8: 108952-108971.
[11] MINERVA R, LEE G M, CRESPI N. Digital twin in the IoT context: A survey on technical features, scenarios, and architectural models. Proceedings of the IEEE, 2020, 108(10): 1785-1824.
[12] RASHEED A, SAN O, KVAMSDAL T. Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access, 2020, 8: 21980-22012.
[13] JONES D, SNIDER C, NASSEHI A, et al. Characterising the digital twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 2020, 29: 36-52.
[14] KRITZINGER W, KARNER M, TRAAR G, et al. Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 2018, 51(11): 1016-1022.
[15] QI Q, TAO F. Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison. IEEE Access, 2018, 6: 3585-3593.
[16] TAO F, ZHANG M, LIU Y, et al. Digital twin driven prognostics and health management for complex equipment. CIRP Annals, 2018, 67(1): 169-172.
[17] NEGRI E, FUMAGALLI L, MACCHI M. A review of the roles of digital twin in CPS-based production systems. Procedia Manufacturing, 2017, 11: 939-948.
[18] CARAGLIU A, DEL BO C, NIJKAMP P. Smart cities in Europe. Journal of Urban Technology, 2011, 18(2): 65-82.
[19] BATTY M. Big data, smart cities and city planning. Dialogues in Human Geography, 2013, 3(3): 274-279.
[20] KITCHIN R. The real-time city? Big data and smart urbanism. GeoJournal, 2014, 79: 1-14.
[21] HOLLANDS R G. Will the real smart city please stand up? Intelligent, progressive or entrepreneurial? City, 2008, 12(3): 303-320.
[22] KANG H, CHEN J, LIANG S, et al. An AI-driven intelligent health assessment system for high-voltage switchgear based on multimodal sensor data fusion. Applied Artificial Intelligence Research, 2026, 2(1).
[23] LIU Z. Explainable machine learning for telecom customer churn prediction and actionable retention strategies. Applied Artificial Intelligence Research, 2026, 2(1).
[24] GAO Z. Data-driven predictive maintenance of permanent magnet synchronous motor systems using explainable machine learning and digital twin architecture. Applied Artificial Intelligence Research, 2026, 2(2).