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Household Digital Twin for Storm Preparedness and Response

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Abstract

Advancements in computational technologies are reshaping the landscape of sustainable smart city planning, enabling data-driven approaches to environmental resilience. A key innovation in this space is the integration of Artificial Intelligence (AI), the Artificial Intelligence of Things (AIoT), and Urban Digital Twin (UDT) technologies. Building on these foundations, this study presents a Household Digital Twin (HDT) system designed to enhance storm preparedness and disaster response at the individual home level. By creating dynamic, virtual replicas of households, the HDT platform enables tailored simulations of hurricane scenarios, offering personalized guidance to families before, during, and after extreme weather events. These simulations model the effects of varying storm intensities on homes and nearby trees, helping homeowners, local governments, and insurance providers assess vulnerabilities, optimize emergency planning, and implement targeted mitigation strategies. Through its ability to deliver proactive, context-specific insights, the HDT system contributes to greater community resilience and supports broader goals in climate adaptation and smart urban infrastructure.

Keywords: Household digital twin, storm preparedness, tree damage simulation, disaster risk reduction

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1. INTRODUCTION

Natural disasters strike abruptly and often leave devastating consequences in their wake, encompassing hydrological, geophysical, and climatological events. Over the past decade, nearly 290 such disasters in the United States have caused an estimated $1.3 trillion in damages, much of it attributed to residential and commercial property losses. In 2023 alone, severe storms accounted for nearly $50 billion in insured damages, with total payouts reaching approximately $530 billion, according to the Insurance Information Institute (III).

Among these disasters, hurricanes remain a persistent and growing threat, affecting both coastal and inland regions through high winds, storm surges, and secondary hazards such as tornadoes (Ayscue, 1996). One often underestimated but highly destructive consequence of hurricanes is falling trees. Tree impacts can puncture roofs, shatter windows, and compromise a home's structural integrity—frequently rendering homes uninhabitable and driving up repair costs (FLORIDA; Gilman et al., 2006). Beyond property damage, fallen trees disrupt power lines, impede emergency access, and pose significant safety risks, further complicating disaster response efforts (Salisbury & Koeser, 2023).

Traditional disaster management emphasizes response, recovery, and preparedness at broad scales. However, the increasing intensity and frequency of hurricanes underscore the need for localized, proactive mitigation strategies. Insurance providers, government agencies, and private stakeholders alike are increasingly supporting technologies that empower households to anticipate risks and take preemptive action.

One promising solution is digital twin (DT) technology, which involves the creation of dynamic, virtual replicas of physical environments to simulate and optimize responses to real-world conditions (Hughes et al., 2023). When integrated into disaster management systems, digital twins contribute to Intelligent Disaster Prevention and Mitigation Infrastructure (IDPMI) by enabling risk assessment, scenario modeling, and decision-making support (Yu and He 2022).

At the municipal level, urban digital twins (UDTs) have demonstrated value in enhancing hazard response and crisis management. These city-scale platforms often combine artificial intelligence (AI) and information and communication technologies (ICT) to model complex infrastructure systems and support data-driven planning (Fan, Zhang, Yahja, & Mostafavi, 2021). T However, these systems typically operate at a macro scale and do not offer the personalized insights needed by individual households.

This study introduces a Household Digital Twin (HDT) platform designed to address predictable natural disasters—particularly hurricanes—at the micro scale. Leveraging advanced simulation technologies, the HDT models the potential impacts of hurricanes on homes and surrounding trees, offering personalized, property-specific mitigation strategies. For example, homeowners can assess risks from nearby unstable trees and take preventive actions such as pruning, removing weak limbs, or reinforcing vulnerable structures. These models could be hosted by insurance providers or local governments, with potential cost savings from reduced claims and emergency relief.

Unlike UDTs, which focus on citywide planning and environmental sustainability (Bibri, Huang, & Krogstie, 2024; Mishra, 2023), the HDT centers on localized risk management and household resilience. It serves as a critical bridge between large-scale disaster simulations and individual preparedness strategies, contributing to a more holistic disaster management ecosystem.

In the broader context of increasing AI and IoT integration within smart cities (Gourisaria et al., 2022; Zaidi, Ajibade, Musa, & Bekun, 2023), the development of household-level digital twins represents a transformative shift in disaster preparedness. Between late 2022 and mid-2024, approximately 1.1% of U.S. households were displaced by disasters—primarily hurricanes (Paul et al., 2024). The high economic losses and vulnerability often result from poor coordination and underinvestment in preparedness (U.S. Chamber of Commerce, 2025).

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This research presents a scalable and intelligent Household Digital Twin platform that simulates hurricane impacts in advance, enabling homeowners, local authorities, and insurers to assess vulnerabilities and implement proactive risk mitigation strategies. By providing predictive insights and actionable recommendations, the HDT contributes to building resilient, disaster-ready communities and supports global efforts to harness digital technologies for climate adaptation and risk reduction.

2. RESEARCH BACKGROUND

Digital Twin (DT) technology, first conceptualized in *Mirror Worlds* by David Gelernter (1991), refers to the creation of dynamic, virtual replicas of physical systems or entities. These digital counterparts enable real-time simulation, monitoring, and data-driven decision-making. DTs are typically categorized into four types—Product Twins, Process Twins, System Twins, and Human Twins—each designed to optimize specific operations and interactions (Juarez, Botti, & Giret, 2021; Boschert, Heinrich, & Rosen, 2018). By integrating operational and engineering data, digital twins evolve in tandem with their physical counterparts, offering deep insights for system analysis, planning, and user engagement.

Within urban contexts, Urban Digital Twins (UDTs) serve as virtual replications of a city's social, environmental, and infrastructural systems. They are used to simulate, predict, and manage real-time urban processes—including transportation, energy distribution, and emergency response—thus enabling more informed governance and planning (Marçal Russo et al., 2025; Zhu & Jin, 2025). UDTs form a foundational component of smart city ecosystems, which leverage interconnected technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and digital platforms to improve urban sustainability, mobility, and citizen-centric services (Ersan et al., 2024; Mohammadi & Taylor, 2017; Vessali et al., 2022).

Smart City Digital Twins (SCDTs) advance this vision by integrating data from IoT sensors, geospatial tools, and real-time communication systems to model city-wide dynamics. These platforms allow for proactive resource management, predictive analytics, and enhanced disaster response. Technologies such as LiDAR, drones, and augmented reality (AR) further extend their capabilities, supporting applications ranging from flood modeling to evacuation planning (Fan, Zhang et al., 2021; Faliagka et al., 2024).

An essential component of SCDTs is the ability to conduct scenario-based simulations. Tools like interactive GeoData Frames enable stakeholders to visualize the potential impacts of various emergencies at neighborhood or block levels (Gkontzis et al., 2024). Past disasters, such as Hurricane Katrina, underscore the importance of incorporating inclusive and community-oriented approaches into disaster planning frameworks (Patterson, Weil, & Patel, 2010). Models such as the Ontology-based Decision Model and Notation (oDMN) (Horita et al., 2016) and the Asian Disaster Preparedness Model (ADPC, 2015) highlight the need for integrated, system-level thinking in adaptive disaster response strategies. SCDTs surpass traditional disaster management tools by enabling holistic views of urban risk and resilience. Projects like METACITIES exemplify the transformative potential of UDTs in optimizing urban transport, emergency response, and environmental management. However, despite their promise, widespread adoption of UDTs faces several challenges:

- Technical Barriers: Lack of standardized data models and limited interoperability across systems.
- Ethical and Governance Issues: Concerns around privacy, transparency, and data governance.
- Economic Constraints: High initial costs of digital infrastructure—such as intelligent sensors, 3D modeling tools, and data centers—pose barriers for disaster-prone but financially constrained regions (GovPilot, 2024; Hexagon, 2025; PwC, 2023; World Economic Forum, 2023).
- Stakeholder Coordination: Effective implementation requires cross-sector collaboration between technologists, policymakers, urban planners, and local communities.

To address these issues, hierarchical digital twin frameworks have been proposed. These structured architectures facilitate seamless data integration, interoperability, and real-time coordination across system layers—from municipal to household levels (Ball et al., 2025; Finke et al., 2023). At the same time, inclusive, people-centric approaches are critical for building trust, ensuring equity, and encouraging stakeholder buy-in (Bibri et al., 2024; Lu et al., 2020).

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As urban populations continue to grow and climate-related disasters increase in frequency and intensity, integrating digital twin technologies into smart city infrastructure becomes increasingly essential. While most research and development has focused on city-scale applications, this study extends digital twin principles to the household level.

Trees are among the leading causes of property damage during hurricanes, often falling on homes, vehicles, and power lines due to high winds and waterlogged soil (Peterson, 2000; Gardiner et al., 2016). While hurricanes also cause flooding and structural failures, tree blowdowns are particularly suitable for simulation at the household level due to their visibility, measurability, and direct mitigation potential via pruning or removal. The focus on trees enables practical, user-driven interventions and supports early-stage validation of digital twin technology in disaster scenarios (Gilman et al., 2006). Future expansions of the HDT will incorporate additional hazards such as flooding and structural damage.

The following section presents a novel Household Digital Twin (HDT) platform—designed to enhance disaster preparedness through hyper-local risk modeling, community engagement, and proactive mitigation measures. By focusing on individual homes and surrounding environments, the HDT aims to fill a critical gap in existing disaster management systems and contribute to more resilient, technology-enabled communities.

3. HOUSEHOLD DIGITAL TWIN (HDT) DESIGN

The history of human intervention in complex systems highlights a critical lesson: sustainable and effective solutions require a deep understanding of the systems they intend to improve (Lawther, 2016). In disaster response, a promising path forward involves leveraging autonomous computational systems to manage complex, ethically charged, and time-sensitive tasks. One illustrative example is the Slándáil Social Media Monitor, a system that enhances disaster communication by integrating public input with official emergency management operations. It addresses the so-called "Good Will Hazard," where uncoordinated efforts by well-meaning individuals can lead to redundancy, resource waste, or critical service gaps (Hayes & Kelly, 2018). By aligning public contributions with official protocols, such systems increase overall response efficiency.

In this ecosystem, individual households are not passive entities—they are critical actors. Alongside governments, insurers, and utility providers, families play a direct role in preparing for and responding to disasters. To analyze and structure this interaction, Activity Theory (AT) serves as a robust framework. AT, a descriptive meta-theory of human behavior, examines how individuals and communities interact with tools, environments, and shared goals over time (Kaptelinin & Nardi, 2012; Kuutti, 1996). Its emphasis on tool-mediated, context-driven activity makes it particularly well suited for digital twin systems, which integrate technical interfaces, environmental data, and human decision-making.

3.1 Conceptual Design

Figure 1 illustrates the conceptual design of the household digital twin (HDT), developed for disaster preparedness. This design is grounded in Engeström's (1999) Activity System Model, highlighting the intricate relationships and interactions within the activity system.

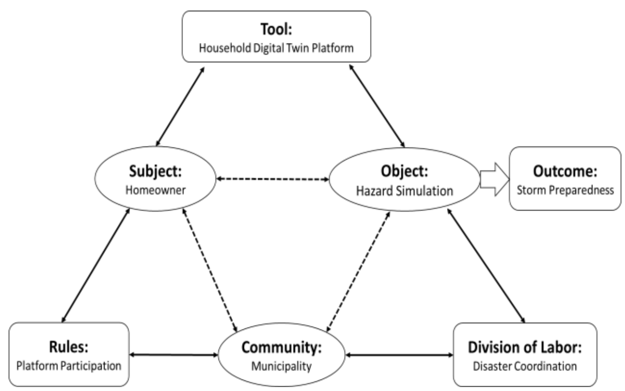

Figure 1. Conceptual design

Each household user can interact with the digital twin system, which simulates catastrophic events such as the impact of severe weather on trees and nearby areas. This interaction occurs through a web platform that is integral to the proposed HDT system. The community within a municipality, comprising households, local officials, utilities, and other stakeholders, collectively forms the operational ecosystem of this framework. The division of labor within the HDT system delineates the responsibilities of each stakeholder in hazard simulation and disaster preparation. Cooperation between families and stakeholders is governed by disaster coordination regulations, ensuring a cohesive response. The system is driven by the overarching goal of providing effective response recommendations, facilitating proactive disaster mitigation.

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3.2 Architectural Design

The origin of digital twin technology traces back to NASA's Apollo missions in the 1960s, where real-time digital simulations of spacecraft were used to troubleshoot failures from Earth. The formal concept was later introduced by Michael Grieves in 2002 in the context of Product Lifecycle Management (PLM) at the University of Michigan.

Today, smart homes and connected environments use similar principles—combining IoT devices, real-time sensors, and cloud-based platforms to model physical conditions. Figure 2 illustrates the architectural design of the HDT system, showing the key components and communication pathways between stakeholders.

A key component of the system is the core simulation module, which leverages a digital twin modeler to replicate the effects of catastrophic events on households and their immediate surroundings. This module analyzes a range of response strategies and provides users with actionable insights tailored to their specific conditions. For example, during hurricane scenarios, the web platform presents simulation outcomes to household users, visualizing potential impacts under varying storm intensities. These simulations are powered by data stored in the database module and are continuously updated with real-time inputs from users.

Household digital twin users typically consist of families or individuals living in smart homes equipped with IoT devices such as thermostats, environmental sensors, connected appliances, cameras, and health wearables. These devices enable real-time interaction with the system, supporting a seamless flow of data and feedback. When users report issues or complete recommended mitigation actions, service providers and municipal officials are automatically notified, allowing for prompt coordination and assistance. This collaborative framework enhances both individual preparedness and collective disaster resilience, fostering a proactive approach to risk reduction at the household level.

3.3 Logic Design

The logic design of the Household Digital Twin (HDT) system, as illustrated in Figure 3, outlines the operational flow from data collection to decision-making. The system leverages LiDAR technology to generate high-resolution digital maps of each region, capturing detailed structural and environmental features of residential properties. This geospatial data, combined with user-provided inputs about household conditions, is stored in a centralized database that serves as the foundation for hazard simulations. Using this integrated dataset, the simulation module forecasts the potential impacts of various hurricane scenarios—such as differing storm categories—well in advance of hurricane season. The simulation results are stored and passed to a recommender system, which generates personalized preparedness plans for each household.

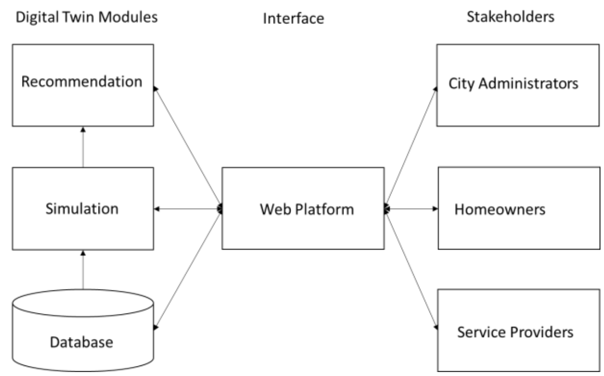

Figure 2. Architectural Design

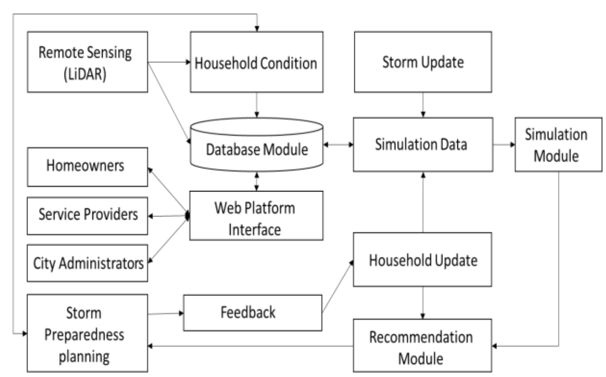

Figure 3. Logic Design

As users implement the suggested actions, such as reinforcing structures or trimming hazardous tree limbs, their feedback is recorded, updating the digital twin's state. This, in turn, retriggers simulations and enables the system to refine future recommendations based on real-time behavioral and environmental data. To ensure that the system reflects current conditions, users can notify the platform upon completing tasks, prompting new assessments. In parallel, service providers, city officials, and homeowners can be alerted when follow-up actions—such as debris removal—are needed.

HDT functions as a mediating tool that links individual households with municipal systems, creating a coordinated ecosystem for storm

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preparedness. Each component reflects the principles of activity theory, in which the subject (household), object (disaster mitigation), and community (stakeholders) interact within a context-driven, tool-mediated structure to achieve collective resilience outcomes.

4. PROTOTYPE DEVELOPMENT

The Household Digital Twin (HDT) prototype demonstrates how interactive storm simulations can assist homeowners in visualizing hurricane impacts on household trees and testing mitigation strategies to reduce damage. While traditional assessment methods offer broader and quicker evaluations, HDT provides granular, dynamic insights that complement these approaches by addressing complex, site-specific risks. To validate the system's design, a working HDT prototype was developed to assess interventions for reducing structural damage caused by tree blowdowns—an all-too-common consequence of hurricanes. These tropical storms frequently result in fallen trees and branches, causing significant property damage and power outages. As shown in Figure 4, the simulation interface enables homeowners to visualize storm impacts on trees adjacent to their property. Users can interactively adjust environmental variables such as wind speed, direction, and precipitation, and virtually prune trees to assess the effectiveness of different mitigation actions.

Figure 4. Simulator Layout

Simulations were conducted using the HDT system to model tree behavior under various hurricane conditions, using typical residential species such as oaks as representative cases. The simulation results provide homeowners with tailored recommendations—such as targeted pruning—to reduce tree-related risks during severe weather events. The current prototype focuses on individual tree modeling; scaling to simulate multiple trees or compound hazards will require more advanced modeling of tree-to-tree and tree-to-structure interactions. Emerging digital twin technologies that integrate high-resolution 3D models with physics-informed AI can enable these more complex simulations, allowing homeowners to manage risk from clustered trees or multiple environmental variables more effectively.

The HDT platform is hosted on a centralized application server that allows users to configure simulation parameters, review projected outcomes, apply recommended actions, and update tree status. Leveraging LiDAR data, homeowners can input or verify detailed attributes such as tree species, leaf shape and texture, number of branches, age, trunk diameter, height, and proximity to the house. Table 1 outlines the input parameters used in modeling a representative neighborhood oak tree for the simulation.

Parameter	Value	Model
Type of tree	Oak	
Shape of leaves	Oblong	
Type of leaves	Flat	
Texture of leaves	Smooth	
Trunk diameter	2 feet	
Number of branches	9	
Age of tree	12 years	
Distance from house	15 feet	
Height of tree	14 feet	

Table 1. Simulation parameters for a neighborhood Oak tree

LiDAR imaging was used to capture treetop structures and outline individual tree crowns. Techniques such as pouring algorithms and vector-based treetop identification were employed to define crown geometry accurately (Koch et al., 2006). This data was used to generate community-scale digital models, as shown in Figure 5, representing both buildings and surrounding vegetation. These models enable realistic and localized storm impact simulations, adjusting for wind direction, speed, precipitation, and storm category.

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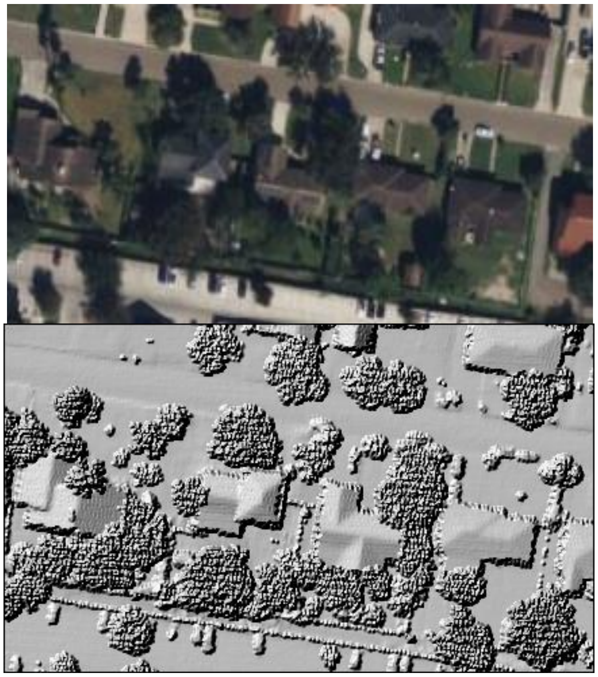

Figure 5. LiDAR surface view of houses and surrounding trees

To quantify wind forces acting on trees, the simulation applies the formula:

$$F = C_d \cdot r \cdot a \cdot U^2,$$

where C_d is the momentum absorption coefficient (varies by tree type), *r* is air density, *a* is frontal area, and *U* is wind speed (Gardiner et al., 2016). Precipitation further affects tree vulnerability—saturated soil increases the likelihood of uprooting, while dry soil makes trees more prone to stem breakage (Peterson, 2000).

Table 2 presents calculated force thresholds and response outcomes for three common tree types—oak, pine, and palm—under Category 2 hurricane conditions (100 mph winds and 8-10 inches of precipitation). C_d values for pine and palm trees are lower than that of oak, indicating reduced resistance to wind momentum. Frontal area values also vary depending on trimming status.

Tree type	C_d	*r*	*a*	*U*	F= $Cd \cdot r \cdot a \cdot U^2$	Precip. (in)	Up-root	Stem Break
Oak	1	1	80%	100	8000	10	1	0
Pine	0.8	1	100%	100	8000	8	0	1
Palm	0.5	1	100%	100	5000	10	0	0

Table 2. Tree Damage Scenarios

Damage outcomes are determined by comparing calculated wind forces to predefined uprooting and stem breakage thresholds. For example, under 100 mph wind and 80% frontal density, the oak tree's wind force reaches 8000 units—sufficient for uprooting if the soil is saturated. These simulations help users assess which trees are most at risk and inform preventive actions such as trimming or removal. While current models focus on tree force thresholds, more comprehensive assessments would require integration of diverse environmental and structural parameters, along with scalability to broader ecosystems.

Tree simulations were developed using TreeIt and rendered using the Godot Game Engine, enabling lifelike reactions to wind forces across different species. As illustrated in Figure 6, each tree type reacts differently based on its structure, trimming, and environmental conditions.

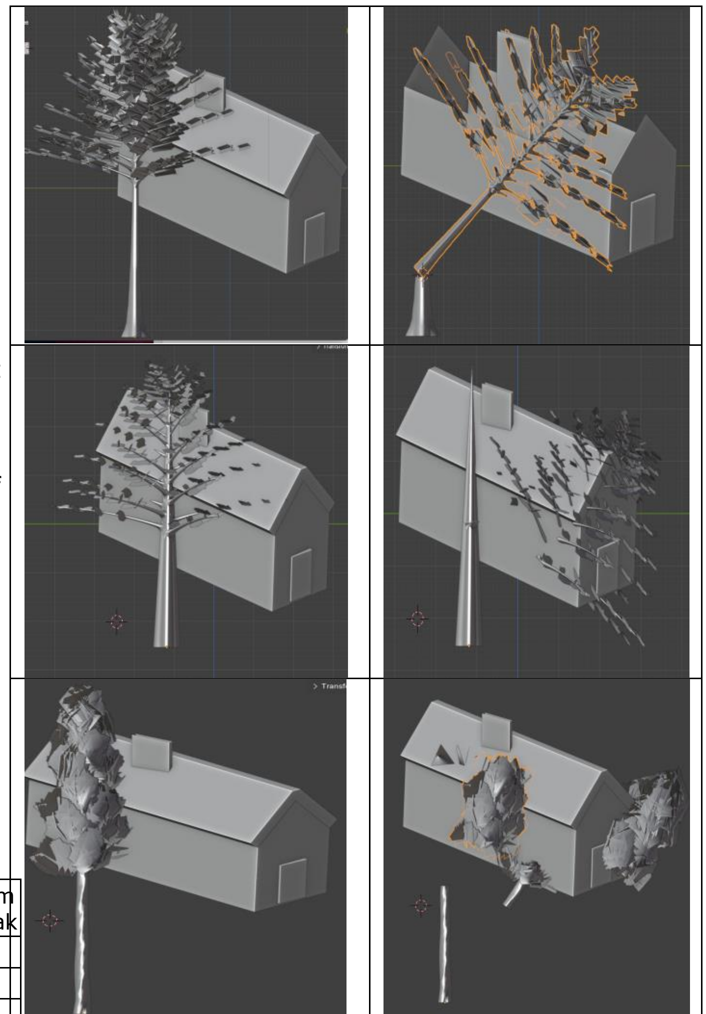

Table 6. Simulation Demonstration

Figure 7 illustrates how tree trimming percentages (ranging from 10% to 50%) affect outcomes under varying hurricane categories. The trimming control in the simulation interface

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allows homeowners to observe risk levels before and after taking action.

Figure 7. Effects of Tree Pruning

The web platform was developed using React, a JavaScript library well-suited for modular interfaces and real-time interactions. TailwindCSS was used for styling, and GreenSock Animation Platform (GSAP) powered the dynamic animations of tree movement. Lottie React was integrated to visualize house damage through real-time, animated sequences triggered by simulated wind speeds. Server-side rendering was handled by Next.js, ensuring optimized performance across devices.

The interface includes three primary controls: a wind speed slider (1–120 mph), a precipitation bar to model rainfall intensity, and a tree trimming percentage selector. Together, these elements enable users to explore complex scenarios interactively, reinforcing the importance of early mitigation strategies and informed decision-making at the household level.

To assess the accuracy of the simulation, the wind force outputs and resulting tree responses were cross-validated using damage thresholds reported in empirical studies of hurricane-related tree damage. For example, the calculated uprooting and stem breakage forces align with those observed in Gardiner et al. (2016) and Peterson (2000), who documented threshold wind speeds and precipitation levels associated with typical tree failures. Although full-scale real-world validation is ongoing, preliminary comparisons with historical damage from Hurricanes Katrina and Irma confirm that the force calculations and tree failure patterns simulated by the HDT prototype fall within reported empirical ranges (Byrne & Mitchell, 2013). Future work will include field deployment and post-hurricane observational studies to validate and refine simulation accuracy.

5. IMPLEMENTATION PATHWAY

Effective implementation of the Household Digital Twin (HDT) system requires coordinated collaboration among multiple stakeholders, each playing a pivotal role in reducing hurricane-induced tree damage to homes. These stakeholders include homeowners, insurance companies, local governments, tree care service providers, and community leaders. Within the HDT simulation framework, insurance companies assess property risk and incentivize mitigation; local governments oversee system deployment, resource allocation, and regulation enforcement; service providers implement recommended actions such as pruning or removal; and community leaders promote adoption, awareness, and stakeholder engagement to enhance disaster resilience.

A core strength of the HDT system is its ability to forecast tree-related vulnerabilities and guide timely interventions. For example, systems that monitor tree health in real time—using IoT-based sensors to track temperature, soil moisture, decay, and structural integrity—can be integrated with HDT simulations to enhance predictive accuracy (Patil et al., 2025). Similarly, advanced monitoring networks that model tree hydraulic responses to climate stressors provide insights into long-term growth dynamics and vulnerability (Steppe & Schaepdryver, 2016). These data streams allow the HDT to move beyond static simulations, enabling dynamic, weather-informed decision support for both homeowners and municipal responders.

5.1 Stakeholders

Homeowners are the primary users and beneficiaries of the HDT platform. By engaging with the simulation interface, they can assess the vulnerability of trees based on wind exposure, species characteristics, and proximity to built structures. The system allows detailed input of tree-specific data—such as species, age, trunk diameter, canopy density, and distance from buildings—enabling personalized recommendations. Dense canopies, which behave like sails during high winds, are flagged by the system as high-risk. In such cases, HDT recommends targeted pruning to improve wind flow and tree stability. These actionable insights empower homeowners to proactively reduce the risk of tree-related property damage before a hurricane strikes.

Insurance companies benefit from HDT's data-driven risk models, which allow for more granular assessment of wind vulnerability on a per-property basis. Simulation data can be used to adjust premium pricing and encourage risk-reducing behavior among policyholders. Insurers may also offer discounts or incentives for proactive measures—such as tree trimming—aligned with HDT recommendations. By collaborating with local governments, insurance providers can help develop community-based mitigation frameworks and risk communication strategies.

Local governments play a critical role in institutionalizing the HDT system across communities. Simulation outputs at the neighborhood scale help identify high-risk areas and inform the prioritization of public mitigation efforts. Municipal authorities can also leverage the system to support urban forestry policies, establish safe tree-planting guidelines, and promote routine tree maintenance. Adoption can be further supported through educational campaigns, subsidies for tree services, and regulatory updates that mandate safe distances and trimming practices.

Tree care service providers are responsible for implementing HDT-generated recommendations. These professionals offer pruning, trimming, or removal services tailored to the simulation's output and help verify tree characteristics during input collection. Integration with the HDT platform supports efficient service scheduling, prioritization of high-risk cases, and documentation of completed work. Service providers also contribute valuable on-the-ground data—such as tree health indicators and regional climate patterns—that improve the simulation engine's local accuracy.

Community leaders are essential for building trust, raising awareness, and fostering grassroots engagement. They can organize public workshops, host neighborhood risk assessments, and facilitate collaboration among residents, service providers, insurers, and public officials. Their leadership helps ensure that HDT deployment is inclusive, resonates with local needs, and supports culturally sensitive disaster preparedness strategies.

Effective deployment of the HDT system relies on this multi-stakeholder alignment, creating an integrated ecosystem of data exchange, risk reduction, and responsive action. When stakeholders coordinate around shared resilience goals, HDT's impact expands—supporting policy reform, smarter urban planning, and resource-efficient disaster mitigation.

5.2 Proposed Deployment Strategy

A phased rollout of the HDT system is envisioned to ensure feasibility, adaptability, and stakeholder engagement across diverse contexts.

Phase 1 (0–6 months): Launch a small-scale pilot in a hurricane-prone municipality, targeting 50–100 households with varying tree profiles. Estimated costs of $100–200 per household will cover LiDAR mapping, app configuration, and coordination with tree service providers. Stakeholder feedback will be collected to refine system features and usability.

Phase 2 (6–18 months): Expand implementation within the same municipality based on Phase 1 outcomes. This phase includes formal partnerships with insurance providers and local governments. Municipalities may fund infrastructure and public outreach, while insurers offer premium discounts to incentivize homeowner participation. Broader public engagement and school-based tree awareness programs can be introduced.

Phase 3 (18–36 months): Regional scale-up through integration with smart city platforms and environmental monitoring systems. HDT will be linked with IoT-enabled weather stations and urban planning dashboards. Cost-benefit projections suggest that a 10% reduction in tree-related claims during hurricanes could yield savings exceeding $1 million for insurers and municipal emergency services (PwC, 2023).

These phases are designed to balance upfront investment with measurable resilience and economic benefits. Pilot deployments will also serve as testbeds for comparing simulation outputs with actual storm damage records and tree failure data, creating a continuous feedback loop that strengthens model reliability.

Looking ahead, HDT will also inform long-term planning decisions, such as optimal tree spacing, species selection, and zoning strategies in residential areas. As environmental conditions evolve due to climate change, the platform will adapt through regular data collection, scenario testing, and stakeholder feedback.

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5.3 Addressing Implementation Challenges

Despite its potential, successful HDT deployment must overcome several barriers. Scalability remains a key concern, as the system must be tailored to diverse urban, suburban, and rural contexts. Integration with existing smart home systems, insurance frameworks, and municipal planning tools requires standardization and interoperability. Predictive accuracy may vary across different tree species, topographies, and environmental conditions, necessitating continuous calibration and validation. Additionally, widespread adoption depends on addressing concerns around cost, digital accessibility, data privacy, and stakeholder trust. Ensuring equitable participation—particularly in historically underserved communities—will be essential to realizing the full societal benefits of the HDT system.

In summary, the HDT implementation pathway emphasizes an ecosystem approach—blending advanced simulation technologies with real-world stakeholder collaboration. Through phased deployment, adaptive feedback, and integration with broader resilience initiatives, HDT offers a transformative tool for reducing hurricane-related tree damage and strengthening community preparedness.

6. CONCLUSION AND FUTURE RESEARCH

This study addresses the growing need to reduce house damage caused by tree blowdowns during hurricanes—an increasingly critical issue as climate change amplifies the severity of tropical storms. Hurricanes often result in trees or large branches being uprooted, causing extensive property damage, blocked access routes, and widespread power outages. In response to this threat, a Household Digital Twin (HDT) prototype was developed to simulate how trees respond to different hurricane conditions when located near residential structures. Using the Godot game engine, the prototype enabled interactive visualization of hurricane scenarios, allowing users to test how factors such as wind speed, precipitation, and pruning influence the likelihood of tree failure and damage to homes.

The prototype represents a foundational step in demonstrating how digital twins can be used for personalized, site-specific disaster mitigation. By integrating user-defined parameters and enabling real-time interaction, the HDT platform empowers homeowners to understand vulnerabilities and take preventive measures. As the system evolves, incorporating additional tree species, regional vegetation types, and structural layouts will expand its applicability. Over time, data collected from user interactions can be used to refine model behavior and enhance simulation accuracy. Furthermore, the validation of simulation results against historical hurricane damage—following methodologies used in prior studies (Byrne & Mitchell, 2013; Gardiner et al., 2016; Guan et al., 2022)—will be essential to ensure predictive credibility and stakeholder confidence.

Future research will focus on several key areas to extend the capabilities of the HDT platform. First, the development of more detailed and biologically accurate tree models is necessary to reflect species-specific responses to wind and precipitation. These models should incorporate variables such as growth stage, canopy density, soil saturation, and trunk flexibility, which influence tree stability under storm situations. Second, expanding customization options for different home types and lot configurations will enable more tailored risk assessments and more relevant recommendations for diverse users.

Another important direction involves simulating interactions between physical infrastructure and social systems. Understanding how tree-related disruptions cascade into impacts on transportation, emergency response, and energy networks will provide a more holistic comprehensive view of disaster resilience. Incorporating these dynamics into the HDT framework can help inform coordinated community-level planning and preparedness strategies.

Additionally, integrating real-time environmental and smart home data will significantly enhance the responsiveness and situational awareness of the system. Drawing on inputs from IoT sensors—such as wind gauges, rain monitors, and soil moisture detectors—can transform the HDT into an adaptive tool capable of updating forecasts and recommendations as weather conditions change. This real-time functionality will be particularly valuable for households and emergency managers preparing for imminent storms.

Finally, continued focus on model reliability, interpretability, and data ethics will be critical for long-term success. Implementing validation protocols, improving user understanding of simulation outputs, and adopting robust data governance practices will help ensure that HDTs

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are not only accurate but also trusted and accessible.

In conclusion, the HDT prototype presented in this study offers a compelling proof-of-concept for how digital twin technology can be applied to reduce property damage from tree blowdowns during hurricanes. With further refinement, including expanded modeling capabilities, real-time data integration, and stakeholder engagement, HDTs hold significant promise as tools for advancing disaster preparedness and urban resilience. As climate risks grow, systems like HDT can play a transformative role in building safer, smarter, and more adaptive communities.

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