Enhancing the resilience of low-income housing using emerging digital technologies

E A Obonyo[1] and L A Ouma[1]

[1] Department of Architectural Engineering, The Pennsylvania State University, 104 Engineering Unit A, University Park, Pennsylvania, 16802, USA

lao5206@psu.edu

Abstract. The research discussed is part of a Belmont Forum disaster risk reduction project aimed at enhancing the resilience of low-income housing. This paper examines feasibility and viability of using emerging digital technologies to enhance the resilience of low-income housing based on requirements of resource constrained, low-lying coastal areas in East Africa. The authors focus on the need to facilitate data and knowledge sharing across domains to: 1) reduce or avoid the potential property loss from flooding events through mapping the interdependencies and interconnectedness across natural and human systems; 2) coordinate the provision of temporary shelter for displaced victims, and 3) building (back) better during the recovery phase. The deployment of Artificial Intelligence, Internet of Things, BIM, Digital twin, VR/AR in disaster risk management is still an emerging area of research. In general, cutting-edge digital technologies are deployed as standalone solutions to address existing data and knowledge sharing needs that are unique to a sub-group of stakeholders. A more holistic and comprehensive solution will require an integrative framework that supports the seamless flow of information across the stakeholders. We propose to address this need through an artificial intelligence enhanced data, information and knowledge sharing platform that synthesizes content into actionable insights

1. Introduction

The research discussed in this paper is part of a Belmont Forum disaster risk reduction project that seeks to address this need through generating use-inspired, interdisciplinary evidence. It is based on selected use cases from flood prone coastal parts of Kenya and Tanzania. The discussion presented in this paper specifically focus on the need to facilitate data and knowledge sharing across domains to concurrently: 1) reduce or avoid the potential property loss from flooding events through mapping the interdependencies and interconnectedness across natural and human systems; 2) coordinate the provision of temporary shelter for displaced victims is provided promptly, and 3) building (back) better quickly during the recovery phase.

Significant efforts have been invested in generating data, knowledge and information that can be used to coordinate disaster risk management work across the mitigation, preparedness, response and recovery phases [1, 2]. These are exemplified by the adoption of UN's the Sendai Framework, a disaster risk reduction and management framework for recording and monitoring disaster globally. Within the US' Federal Emergency Management Agency's (FEMA) maintains a database for historic disaster and resilience measures based on lessons learnt. This avails a variety of information that can be used to coordinate disaster risk management at the national, regional, and local community level.

Emerging digital technologies have improved access to vital disaster-related data, information, and knowledge that can be used to support evidence-based policy making [3]. This notwithstanding, much more work needs to be done. As of 2015, close to 1 million people lost their lives because of natural disasters while approximately 1.4 million sustaining injuries. Approximately 23 million lost their property with a cumulative economic loss of more than $ 3.24 trillion. With the rising levels of greenhouse gas emissions, extreme weather events resulting from climate change will continue to be experienced globally. This presents a clear indication of a rising trend in natural disasters [4, 5]. A range of disasters including floods, hurricanes, typhons, violent storms, earthquakes, collapsed infrastructure, social unrest, conflicts, forced migration have intersected with the ongoing Covid-19 pandemic. These intersecting disasters pose the greatest threat to the poor and most vulnerable in society as they are more likely to live in homes that are more vulnerable to the impact of these disasters [6].

Information overload limits coordination efforts. Significant delays to disaster response efforts have been attributed to the lack of robust integration frameworks. The inconsistent flow of data, information and knowledge among different stakeholders is a constraining factor limiting coordination of resources across the different domains of disaster risk management [7]. The existing information that could be used to coordinate their efforts is distributed across different platforms as lengthy and comprehensive reports displaying complex numerical figures and tables. Many non-academic stakeholders find this information difficult to locate and consume [3, 8, 9].

There is also an additional community engagement challenge limiting uptake of technologies that could enhance the resilience of low-income housing. Potential solutions must be conceptualized and co-developed in partnership with the impacted communities. Conventional disaster risk reduction characterized by top-down approach fail to capture the social, cultural, and economic dynamics and vulnerabilities of communities in relation to disaster risk management. The implementation of solutions that rely on reaction to the aftermath of the disaster rather than taking a human in the loop approach. Uptake of these solutions can be scale through a cocreation approach that is backed by lessons learnt from previous efforts [6, 9]. We are learning during the current pandemic that we must move beyond the traditional view of relying on 'hard' engineering and infrastructure solutions in a disproportionate manner. A technology-push approach that is not informed by the lived experiences of these communities cannot generate measurable societal outcomes at scale and in a sustainable manner [10, 11].

Based on an in-depth examination of the deployment of Remote sensing and image capture, Artificial Intelligence, Internet of Things, Building Information Modelling (BIM), Digital twins, Virtual Reality (VR)/Augmented Reality (AR), the authors have established that the challenges outlined in the preceding paragraphs could be addressed using digital technologies. This notwithstanding, their use in disaster risk management is largely limited to standalone solutions that address data, information and knowledge sharing needs for a sub-group of stakeholders. A more holistic and comprehensive solution will require an integration framework that supports the seamless flow of heterogenous information across the applications used by various stakeholders. We propose to address this need through using a concept for a data, information and knowledge management warehouse that could help address the various information needs of multiple stakeholders working towards enhancing the resilience of low-income housing. Various digital technologies have been used at different stages of the disaster risk reduction and management process from the capture and collection of data, sorting, transmission, analysis and sharing. These technologies facilitate generation of sensible information to guide towards minimizing loss and damage [3]. Pertinent content required to make quick decisions, particularly during a disaster, remain scattered in different repositories [9]. During the 2017 US hurricanes, lack of easy access to vital information and knowledge delayed decision making in disaster response efforts [7].

This paper examines the feasibility and viability of using emerging digital simulation, modeling, and visualization tools to enhance the resilience of low-income housing based on the requirements of low-lying coastal areas in Kenya and Tanzania. In the subsequent section, the authors present the systematic review methodology that was used in the research. This is followed by a discussion of key findings from the review. Conclusions are thereafter drawn based on the findings. Recommendations and future research directions based on the gaps identified by this study are presented in the conclusion.

2. Methodology

This study is based on a critique of the state-of-the-art disaster risk management technologies. This desk review was limited to disaster risk reduction efforts within the building sector. The contents of the research papers were scrutinized to identify relevant subject matter experts.

A keywords search was conducted in journal papers and publications platforms including Web of Science, Google Scholar, Science Direct, and Scopus. Google scholar was used to provide an overview of the possible publications for inclusion. A summary of the search criteria and results is shown in table 1.

Table 1: Search criteria and outcomes for reviewed work. Source: authors' construct

Platform	Search criteria	Keywords	Search outcome

Google scholar	Article titles	Natural disasters AND state-of-the-art technologies AND disaster management technologies in buildings AND disaster risk information AND infrastructure disaster resilience AND disaster risk communication	2560
Web of science	All fields	Natural disasters AND technologies AND buildings AND information AND infrastructure year 2021 to 2010	46
Scopus	Title, keywords, abstract,	Natural disasters AND state-of-the-arttechnologies AND disaster management technologies AND disaster risk communication AND infrastructure resilience AND disaster risk information. Limit to engineering	63
Science direct	Research articles, review articles and book chapters. open access	Natural disasters AND state-of-the-art technologies AND disaster management technologies in buildings AND disaster risk information AND infrastructure disaster resilience AND disaster risk communication year 2010 to 2021	79

For the exclusion criteria, the authors did not include research papers that did not directly address the use of digital technologies as part of disaster risk management within the built environment only. Based on the overall search outcome in column 4 of table 1, research papers that focused the technologies without emphasis on disasters were left out in the review. Papers presented in languages other than English were also excluded. A further scrutiny of the journals within Mendeley was performed to eliminate duplications. 40 journal papers that were considered deemed appropriate against this criterion. Additional papers were considered for on concepts elaboration. Overall, a total of 60 sources were included in the in-depth analysis.

3. A critique of cutting-edge technologies in disaster risk management

Several digital technologies can be deployed at different stages to create a data driven knowledge platform based on the available pool of information. Several studies focus on the application of the individual state-of-the-art technologies in disaster risk management for example [6, 12–16]. As previously stated, they have been implemented as standalone solutions. There is a need for additional research on strategies that can be used to advance existing disaster risk management platforms into deliver more data driven knowledge and information decision support tools for use by built environment stakeholders [9, 14]. The analysis does by the authors has identified several opportunities where digital technologies can be used to significantly reduce the risk associated with disaster. There is a specific focus on the technologies that can be deployed within the context of low-income housing.

3.1. Artificial Intelligence (AI)

The growth of data collection and application of complex technologies in capturing real time data has resulted in generation large amounts of information on natural disasters [17]. This information cannot be processed easily by traditional data processing techniques. Intelligent machines and computer programs with human capabilities are utilized to fill this gap. They can be optimized to make sense of the overwhelming data from heterogenous sources. This constitutes the core concept of Artificial Intelligence in disaster risk management [13].

AI can be used in the processing collected data, analysis, and simulation of disaster scenarios for disaster planning and decision making. Using AI techniques, sensible data, predictions and analysis can be done at a rapid pace that matches the sense of urgency associated with disaster risk reduction efforts [18]. AI encompasses machine learning which utilizes various techniques for disaster risk management in analysis, integration of multisource data and communication to the relevant stakeholders. Urban planning and management of built assets in cities is becoming complex due to the unpredictable extreme weather events. [19] presented an integrated information system that utilizes intelligent data extraction from sensors, GIS and GPS systems and Internet of Things to provide early warnings in areas prone to snow melt flooding. Various AI techniques have been used to develop predictive disaster risk models and provide data for disaster management and analysis tools such as the Resilience Analysis and Planning Tool (RAPT) [20].

AI is also applicable in extracting data from databases and voluminous sources for processing to generate desired information and knowledge relating to natural disasters [21]. AI could be used to enhance knowledge sharing through digital twin virtual models. Real time data from physical assets can be collected using remote sensors and hard sensors. This data can be processed and synthesized for use in disaster prediction and simulation. AI can also facilitate the identification of distinct features of spatial data and differentiation of the different elements of the collected data such as surface and asset types including buildings, infrastructure, water bodies and vegetation. This is exemplified by Microsoft's AI for Humanitarian Action Projects that mapped building footprints in selected areas in Uganda and Tanzania. The classification of the data in groups for advance analysis and application can help significantly reduce underlying risks [22]. AI can also facilitate the analysis of the extent and type of damage on structures [14, 19].

Prediction of building damages and interventions to minimize complete failure have also applied intelligent machine learning techniques [23]. The use of deep learning models, Neural Networks, Support Vector Machines and Deep learning for disaster information identification, classification, analysis, prediction, interpretation, and visualization also continue to be a point of research focus [13, 14, 21]. Such tools enhance awareness thus minimizing the fatalities and property loss thus promoting community resilience.AI based machine learning and big data analytics provide a platform for simulation and visualization of disaster scenarios [24, 25].

3.2. Remote sensing and image capture technology

A clear understanding of the sources, severity and impact of the disaster is needed to develop mitigation strategies against disaster loss and damages. Technological advancement currently supports the capture of real time climatic conditions and changes that can be used in predicting potential weather hazards. Satellites and remote sensors are used to collect data and monitor the surrounding conditions of built assets such as changes in water level, moisture, pressure, temperature, wind patterns to detect potential floods, tsunami, earthquake, typhoons, hurricanes, heat waves. Satellites, drones and image sensing technologies are useful in capturing images of assets prior to, during and post disaster. Drones are being actively used in capturing images for rapid mapping, evacuation planning and damaged assessment [11, 14, 21, 26].

NASA's SERVIR, based in Kenya provides remote sensing and imagery data for disaster resilience in Eastern and Southern Africa [27, 28]. The National Oceanic and Atmospheric Administration (NOAA) and similar organizations in several western countries generate data on weather, climate and potential disasters as observed from satellites and remote sensors. The data can be used to develop disaster maps and delineate disaster risk areas. Real time availability of information supports development of disaster resilience tools, strategies, and platforms. Analysis of the data provides information that is vital for various stakeholders' risk reduction efforts [29]. It is worth noting that built environment professionals do not typically access such repositories while making decisions. There is a heavy reliance on historical climate and weather patterns.

Some researchers are working towards address this challenge. Image capture techniques such as drones, Light Detection and Ranging (LiDAR) are powerful tools that provide data for production of disaster maps and 3D city information models for disaster risk simulation and visualization. Drones is an efficient sensing and imagery technology for localized application and has gained popularity due to its affordability, flexibility, and high-resolution output [11, 12, 30]. The extent of damage of built assets and vital infrastructure can be captured using point cloud imagery techniques through laser scanning, autonomous aerial vehicle photography to generate images for modelling. The models could inform reconstruction, retrofitting and design of new assets in affected areas. of existing buildings and infrastructure facilities [26].

3.3. Internet of Things (IoT)

Internet of Things (IoT) comprises an interconnected network systems that can exchange information and communicate over the linked network system facilitating sharing of information. IoT comprises of three major parts, a physical sensor attached to the physical asset, a communication connection system and a visualization system that facilitates the display of the data that is exchanged between the systems [31]. The sensors capture information from the asset onto which they are embedded. The information is shared with the data processing system, which, with application of machine learning techniques, is easily processed and analyzed before it is sent to the visualization system in a manner that the end user can easily interpret. In case of further requirements, the information query is sent back to the data system for review and feedback [21, 32, 33].

Built assets are currently being embedded with sensors which can detect changes in the surrounding environmental conditions. These include changes in air pressure, temperatures, humidity that can be linked to climate change related extreme weather events. Once this information is sent to the system and processed, the activated warning systems or visualizations could enable proactive decision making. The advantage of IoT is that the data can be transmitted in real time [21, 33]. Sensors have also been used to monitor the development of potential points of failures in built assets that are continually exposed to disasters such as earthquakes. This information is transmitted over the network to facility management systems and disaster monitoring data centers for renovation, retrofitting and design decisions in urban planning and design. IoT uses sensors and Radiofrequency Identity Tags can be scanned to share the information with the digital twin of assets for monitoring and management of various emergencies beforehand [34].

3.4. Building Information Modelling (BIM)

Building Information Modelling is a process of collaborative generation of 3-dimensional graphical models of built assets embedded with non-graphical descriptive data that supports decision making in the building and infrastructure assets lifecycle and associated asset management process [35]. Building information models are data rich virtual assets which can be simulated and manipulated in different scenarios digitally to display the potential consequences of disaster response decisions and how they affect the resilience of the built assets [36]. BIM has demonstrated great potential to reduce cost increases due to design issues, save on construction time, avail vital information for facility maintenance and management and eliminate the traditional construction industry inefficiencies. This explains the growth in its adoption. In 2020, the market value of BIM stood at approximately $ 5.4 billion. This growth was characterized with a significant rise of 12.5%. The projected value preposition stands at $ 10.7 billion by 2026 [37]. The onset of COVID-19 drove the need for digital AEC platforms with collaboration among the numerous trades for the design, construction and management of the built environment and related infrastructure and their dynamics [35, 37]. BIM has shown great potential to be used in disaster planning and management for individual assets and integrated city infrastructure [38].

BIM models have been used in the analysis and simulation of the impact of disaster on built assets and prevention strategies for building resilience. BIM models have been used to demonstrate the impact of disaster on the built environment with enhanced visualization of the buildings' underlying risks. A good example is the 'Neighborhood at risk' flood visualization tool. It is a tool for visualization of flood risks to enhance understanding of the underlying housing damage [39]. [40] also dissect on the how BIM models can be used to predict, plan for and enhance recovery efforts in the face of both human and natural disasters. In the study, a thorough review of research relating to BIM and disaster resilience demonstrated that BIM can be used in visualization of disaster planning and evacuation in buildings, flood and earthquake damage impacts and the assessment of damage costs associated with these disasters based on existing virtual models. A BIM-GIS integration can enhance the prediction of flood levels and assess the extent of damage to buildings as studied by [41]. City BIM models rely on the BIM-GIS integration where the city landscape and environment is combined with a series of 3D BIM models of the buildings and infrastructure systems in a common environment to visualize the overall city environment for disaster planning and management purposes [42]. The application can be expanded beyond an individual building level to facilitate the exploration of resilience at the city-scale. This is exemplified by work done by researchers at the Center for the Digital Built Britain. Their large-scale application of BIM models focuses on monitoring the impact of floods on the built infrastructure [43].

3.5. Virtual Reality and Augmented Reality (VR/AR)

Virtual Reality (VR) is an interaction of human viewer with a computer-based simulated virtual environment to experience scenarios based on the manipulations of the simulated virtual environment to enhance understanding and guide decisions [44]. The deployment of VR as a tool for emergency management dates to the 1990s [45]. VR has been identified as a great tool for visualization of disaster situation without the existence of the actual disaster scenario.

Over the years, assistive devices have gained traction as tools that promote proactive action through enabling interactions with a seemingly real environment. Theis is exemplified by Erikson et al.'s [46] detailed visualization of the effect of climate change and sea level rise on the coastal communities. Their application of VR informed multiple stakeholders about the flood hazard sea-level rise posed to the coastal communities'-built assets and infrastructure. The growing capability of the virtual reality is aligned with the need for tools that can be used to proactively plan for emergencies and hazards throughout the building lifecycle [44].

It has been demonstrated that visualization using VR can enhance planning for disaster response and informed rescue and recovery during a disaster [15, 47]. VR can enable stakeholders to explore various interventions easily and assess how each proposal and associated actions could impact the resilience of the built assists during a disaster.

It is worth noting that BIM can be combined with Virtual Reality to generate realistic simulations for fire evacuations in buildings [48].

Augmented Reality (AR) utilizes virtual objects, models, and simulations to create a realistic visualization of the disaster in the real environment of the viewer bringing the interaction into the physical environment [44]. Experiences in other domains can inform practice within the built environment. The advantage that AR offers over the VR is it enables the users to have an interaction with their real physical environment and gain a deeper understanding of the response strategies and accurate means of application during actual disasters [49].

AR has gained popularity in online commerce, where organizations such as IKEA employ this technique to allow buyers to have a realistic view of the appearance of the commodity in their spaces before purchasing. In disaster risk management efforts, AR allows users to understand how a given disaster (such fire, earthquake, floods etc.), may appear in the real-world environment. This can help prompt proactive planning to address the underlying risk factors. how to deal with the situation. Catal et al., 2020 demonstrated the successful application of AR in a stakeholder training program focusing on evacuation of public buildings during an earthquake. Serious game theoretic learning has been used together with the AR/VR visualization to highlight the impact of the decisions and trainings on the best strategies to tackle the predicted danger to the physical assets presented by the natural disaster [44, 49]. Application of the game learning technique drives critical decision making from all the stakeholders based on their specific constraints and experiences while enhancing their proposal for rational solutions [14, 16].

3.6. Digital twins

A digital twin is a descriptive and graphical representation of a physical component and all its contents in a virtual environment therefore facilitating simulations for predictions or analysis of the current or historic behavior of the component throughout its lifecycle [42, 50, 51]. Digital twins allow simulation of all probable weather scenario and generate the possible impacts based on the data attached to the virtual model and predictions based on data from the connected sensors [52]. A digital twin comprises of the physical component, virtual model, connection, data and utilization. The virtual 3D model captures the as-is information in the physical model. This can be linked to the physical model through sensors, scanners, and RFID tags. Drone imaging can be used to collect data for modelling that provide a basis for digital twins for existing assets [53]. The resulted data is sent back to the virtual space to inform the design of the virtual model and allow for simulations and decision support [54].

Digital twins could underpin a holistic approach that provide convergences of a range of disaster related information. Information generated from various sources facilitates an informed analysis of disaster risk to inform decision making by stakeholders in the built environment [14]. There are some similarities between digital twins and cyber-physical systems. The latter are designed to send data back to the physical model [19]. However, unlike cyber-physical systems, digital twins do not necessarily send data back to the physical model or in any way control the performance of the physical model [19].

[55] refers to virtual models with one-way data communication lines as digital shadows rather than an actual digital twin since the latter requires a two-way data exchange and controls. It is worth noting that this feature is desirable because it could improve the efficiency of the digital twin.

Digital Twins increasingly being developed by cities to monitor the impacts of disasters such as floods, earthquakes, hurricanes etc. on the assets could peek at and even exceed 500 by 2025 [56]. Modelling, simulation and visualization of climatic change disaster scenarios is possible within the disaster city digital twins due to availability of real time and historical data attached to the virtual model [52]. The digital twin of Singapore was deployed as a digital 3D representation of the City's built environment [57]. It allows multi-stakeholder planning of the city for resilience and community engagement through visualization, communication, infrastructure utilization and research support to enhance sustainability of the cities and communities

The National Digital Twin program (NDTp) and partners have developed a climate resilience demonstrator interactive application that utilizes the digital twin to provide interconnected infrastructure information sharing to enhance the resilience of infrastructure and communities during floods [43]. The demonstrator facilitates information sharing across network providers based on visualization from the digital twins to locate affected infrastructure systems during flooding scenarios to facilitate planning for deployment of rescue and service restoration during floods.

Some approaches are aligned with need for more localized disaster risk reduction strategies. This is exemplified by community led drone imaging work deployed through Flying labs by WeRobotics [30]. WeRobotics has active Flying Labs in Kenya and Tanzania.

4. Discussion

As outlined in the introduction, some of the key challenges in disaster risk management efforts include the lack of robust data, information, and knowledge integration strategies. Climate action within the fragmented low-income housing sector predicates on inputs from diverse of stakeholders who have different needs and requirements. Cutting edge digital technologies could help reduce losses and impacts of disasters on communities through provision of information and data that is vital for enhancing disaster risk elimination, preparedness to deal with the outcomes and response measures to be adopted. However, any content that is made available to the various stakeholders must be actionable, relevant, and relatable – there is a sense of urgency surrounding decision making in disaster risk reduction efforts. In the preceding section, the authors outlined some exemplary projects that have successfully addressed these requirements. This notwithstanding, a lot of the existing data, information and knowledge remains underutilized in disaster risk management efforts within the lowincome sector domain. The authors contend that the problem is a lack of easily accessible data, information, and knowledge integration platforms. Emerging digital technologies are often deployed as standalone solutions. Less than 2% of the reviewed work focused on technology integration. Approaches that combine the functions and capabilities of remote sensing, AI, IoT, BIM, Digital twin and VR/AR technologies could promote timeline decision making in the low-income housing sector.

Figure 1 depicts the author's proposed concept for a data, information and knowledge management warehouse that could address this problem. The authors have established that existing digital technology ecosystem in both Kenya and Tanzania can provide the infrastructure and support required to deploy the proposed approached. This is exemplified by our synergies with WeRobotics. The first author has also been collaborating with Engineering for Change to support student research projects [58]. These projects will in the near future have a BIM component and will leverage synergies with Autodesk Foundation's regional hub that is headquartered in Nairobi, Kenya.

The proposed platform will integrate content from heterogenous sources. Various stakeholders can access content tailored to their needs and requirements. This enables prompt decision making and action. For example, occupants of structures identified to be at risk would access content on affordable building renovation solutions. Humanitarian actors can extract information that simplifies the process of developing response strategies that are aligned with the needs, capabilities, and priorities of a specific community. The proposed warehouse can also help policy makers to be more transparent with respect to resource allocation priorities for shelter deployment and reconstruction. Built environment researchers and practitioners can derive information that can be used to inform the development or modification of, for example, design manual building standards and codes. Information flow among the stakeholders enhances collaborative approach to disaster management while also allowing them to contribute to the platform based on their experiences in disaster management and response.

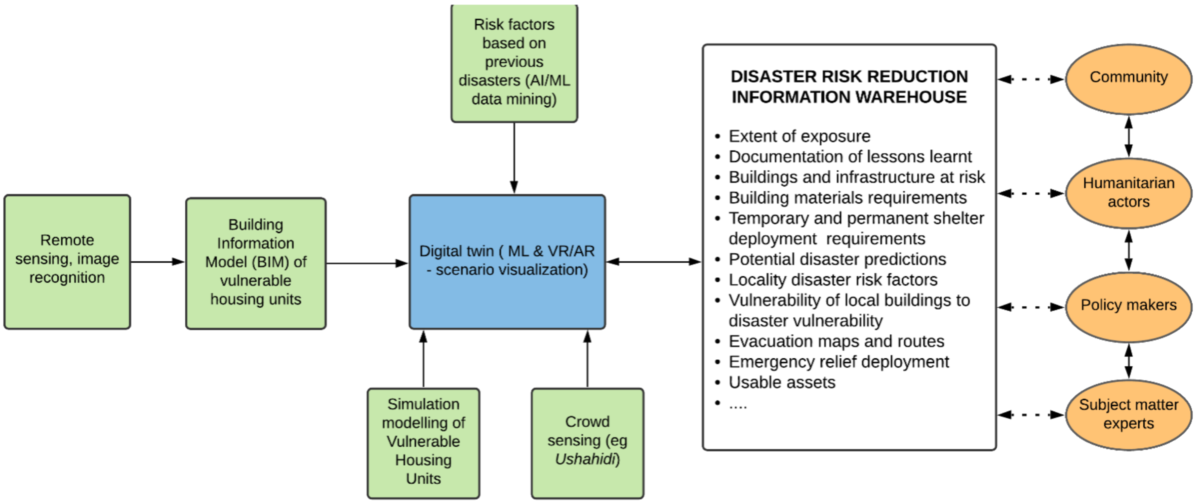

Figure 1: A concept for a data, Information and Knowledge Warehouse for Resilient Low-Income Housing

5. Conclusions and future work

The research discussed in this paper is part of a Belmont Forum disaster risk reduction project aimed at enhancing the resilience of low-income housing based on the requirements of resource constrained, low-lying coastal areas in selected parts of Kenya and Tanzania. The authors have outlined specific ways through which emerging digital technologies can be used to promote proactive planning. They have also outlined the complexities surrounding the sharing of data, information, and knowledge. Many of these technologies have been deployed as standalone solutions. There is, therefore, a missed opportunity with respect to promoting synergies across different stakeholder groups.

Against this backdrop, the authors are developing a data, information and knowledge integration framework that leverages the capabilities of several digital technologies - AI, remote sensing, and image capture, IoT, BIM, VR/AR and Digital twin. Our proposed data, information and knowledge warehouse has been conceptualized as a convergence platform that bridges the existing gaps in the information value chain that can underpin the delivery of resilient, low-income housing. This concept will be advanced further using selected case studies in Dar es Salaam, Tanzania. As part of this work, the authors will also develop an ontological framework. The authors will adapt and refined frameworks from closely related work - see for example, [59, 60].

References

[1] FEMA 2021 Resilience Analysis and Planning Tool *Available from: https://www.fema.gov/emergency-managers/practitioners/resilience-analysis-and planning-tool*

[2] UNDRR 2021 UNDRR Strategic Framework 2022-2015; 1–20

[3] Zheng L et al. 2013 Data Mining Meets the Needs of Disaster Information Management. *IEEE Transhuman-machine Syst;* **43(5)**:451–64 https://ieeexplore-ieee-org

[4] UNDRR 2015 Sendai Framework for Disaster Risk Reduction 2015-2030

[5] World Meteorological Organization 2021 State of the Global Climate 2020 (*WMO-No. 1264)* 1–56 p. Available from: https://library.wmo.int

[6] Imperiale A J and Vanclay F 2021 Conceptualizing community resilience and the social dimensions of risk to overcome barriers to disaster risk reduction and sustainable development

[7] Long B 2018 Hurricane Season FEMA After-Action Report *Hurric Seas FEMA After Action Rep* **65** Available from: https://www.fema.gov

[8] Akter S and Wamba F 2019 Big data and disaster management: a systematic review and agenda for future research. *Ann Oper Res*. **283** 939–59. Available from:

https://doi.org/10.1007/s10479-017-2584-2

[9] Zuccaro G, Leone M F and Martucci C 2020 Future research and innovation priorities in the field of natural hazards, disaster risk reduction, disaster risk management and climate change adaptation: a shared vision from the ESPREssO project. *Int J Disaster Risk Reduct* **51** 101783 Available from https://doi.org/10.1016/j.ijdrr.2020.101783 [10] Ghazvinian A and Leung T 2021 Engineering design recommendations for resilient housing : A case study of Dar es salaam in East Africa

[11] Munawar H S, Hammad A W A and Waller S T 2021 A review on flood management technologies related to image processing and machine learning *Autom Constr.* Dec 1;**132**:103916

[12] Cheng J, Shao Z, Xu T, Wei W, Qiao R and Yuan Y 2021 Experimental research on sintering construction spoil bricks based on microwave heating technology *Environ Sci Pollut Res* **28**(48):69367–80

[13] Dwivedi Y K et al 2021 Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *Int J Inf Manage*. Apr 1 **57** 101994

[14] Fan C, Zhang C, Yahja A and Mostafavi 2021 A Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management. *Int J Inf Manage* **56**(March 2019):102049

[15] Feng Z et al. 2020 An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings. *Adv Eng Informatics.* 2020 Aug 1;**45**:101118

[16] Marome W, Natakun B and Archer D 2021 Examining the Use of Serious Games for Enhancing Community Resilience to Climate Risks in Thailand Available from: https://doi.org/10.3390/su13084420

[17] GFDRR, World Bank and Deltares 2019 Responsible AI for Disaster Risk Management [18] McGovern A et al 2017 Using artificial intelligence to improve real-time decision-making for high-impact weather. *Bull Am Meteorol Soc.* **98**(10):2073–90

[19] Fang S et al 2015 An integrated information system for snowmelt flood early-warning based on internet of things *Inf Syst Front.* **17**:321–35

[20] FEMA 2021 FEMA Hazus Loss Library Available from: https://hazards.fema.gov/

[21] Munawar H S, Mojtahedi M, Hammad A W A, Kouzani A and Mahmud M A P 2022 Disruptive technologies as a solution for disaster risk management: A review. *Sci Total Environ.* **806**

[22] Fleming S 2020 How AI is helping map the world's most vulnerable places Available from: https://news.microsoft.com/on-the-issues/2020/02/13/ai-missing-maps-hot-bing/

[23] Anand V and Miura Y. PREDISM: Pre-Disaster Modelling With CNN Ensembles for At Risk Communities

[24] Grolinger K, Mezghani E, Capretz MAM and Exposito E 2016 Knowledge as a Service Framework for Collaborative Data Management in Cloud Environments - Disaster Domain. *Big Data: Concepts, Methodologies, Tools, and Applications* p. 588–614

[25] Ybañez R L, Ybañez A B, Mahar F and Aurelio M A 2021 Imaging ground surface deformations in post-disaster settings via small UAVs *Geosci Lett* **8:23**. Available from: https://doi.org/10.1186/s40562-021-00194-8

[26] Ding Z, Jiang S, Xu X and Han Y 2021 An Internet of Things Based Scalable Framework for Disaster Data Management. *J Saf Sci Resil* Available from: https://doi.org/10.1016/j.jnlssr.2021.10.005

[27] SERVIR Eastern & Southern Africa 2022 Water Resources and Hydro-Climatic Disaster. Available from: https://servir.rcmrd.org/

[28] Wahome A, Sarbo S and Mbatia W 2014 SERVIR Eastern & Southern Africa Science Overview Regional Centre for Mapping of Resources for Development (RCMRD) Available from: http://www.ku.ac.ke

[29] Kucharczyk M and Hugenholtz C H 2021 Remote sensing of natural hazard-related disasters with small drones: Global trends, biases, and research opportunities. *Remote Sens Environ.* Oct 1;**264**:112577

[30] Tingitana L 2018 Tanzania Drone Pilots Respond to Worse Flooding in 100 Years Available from: https://blog.werobotics.org

[31] Asghar M H 2002 Principle Application and Vision in Internet of Things (IoT)

[32] Adeel A et al. 2019 A Survey on the Role of Wireless Sensor Networks and IoT in Disaster Management. 57–66

[33] Velickov J 2020 Digital twin AI ML - Available from: https://www.linkedin.com/pulse/asset-performance-management-apm-40-digital-twins role-velickov/

[34] Rad M H, Mojtahedi M and Ostwald M J 2021 buildings Industry 4.0, Disaster Risk Management and Infrastructure Resilience: A Systematic Review and Bibliometric Analysis Available from: https://doi.org/10.3390/buildings11090411

[35] Sacks R, Eastman C, Lee G and Teicholz P 2018 *BIM Handbook* Third Edition John Wiley & Sons; 681 p

[36] Garber R 2014 *BIM design: Realising the creative potential of building information modelling* 1st ed. John Wiley & Sons

[37] Markets & Markets 2021 Building Information Modeling Market with COVID-19 impact analysis by Deployment Type (On Premises, Cloud), Offering Type, Project Lifecycle (Preconstruction, Construction, Operation), Application, End user, & Region - Global Forecast to 2026 *Available from: https://www.marketsandmarkets.com/Market Reports/building-information-modeling-market*-95037387.html

[38] Dakhil A and Alshawi M 2014 Client's Role in Building Disaster Management through Building Information Modelling. *Procedia Econ Financ.* Jan 1;**18**:47–54 [39] Headwaters Economics 2022 Neighborhoods at Risk Available from: *https://headwaterseconomics.org*

[40] Khanmohammadi S, Arashpour M and Bai Y 2020 Applications of building information modeling (BIM) in disaster resilience: Present status and future trends. *Proc 37th Int Symp Autom Robot Constr ISARC 2020 From Demonstr to Pract Use - To New Stage Constr Robot.* (Isarc):**1380**–7

[41] Amirebrahimi S 2015 Flood damage to building: A Data Model for Integrating GIS and BIM for Assessment and 3D Visualisation of Flood Damage to Building

[42] Cureton P and Dunn N 2021 Digital twins of cities and evasive futures. *Shape Smart Better Cities* Jan 1;267–82

[43] Digital Twin Hub 2021 Climate Resilience Demonstrator *Available from: https://digitaltwinhub.co.uk/projects/credo/technical-overview/*

[44] Zhu Y and Li N 2021 Virtual and augmented reality technologies for emergency management in the built environments: A state-of-the-art review *J Saf Sci Resil* Mar 1;**2(1)**:1–10

[45] Beroggi G E G, Waisel L and Wallace W A 1995 Employing virtual reality to support decision making in emergency management. Saf Sci. Jul 1;**20(1)**:79–88

[46] Erikson L et al 2018 Tools for Assessing Climate Change-Driven Coastal Hazards and Socio Economic Impacts. J Mar Sci Eng **6**:76. *Available from: www.mdpi.com/journal/jmse*

[48] Rüppel U and Schatz K 2011 Designing a BIM-based serious game for fire safety evacuation simulations. *Adv Eng Informatics* Oct 1;**25(4)**:600–11

[49] Mitsuhara H, Tanimura C, Nemoto J and Shishibori M 2021 Expressing Disaster Situations for

Evacuation Training Using Markerless Augmented Reality. *Procedia Comput Sci.* Jan 1;**192**:2105–14

[50] Grieves M and Vickers J 2017 Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems

[51] Kritzinger W, Karner M, Traar G, Henjes J and Sihn W 2018 Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine.* Jan 1;**51(11)**:1016–22

[52] Kosowatz J 2021 Smart Cities Look for Digital Twins *Available from: https://www.asme.org/topics-resources/content/smart-cities-look-for-digital-twins*

[53] Costabile P, Costanzo C, De Lorenzo G, De Santis R, Penna N and Macchione F 2020 Terrestrial and airborne laser scanning and 2-D modelling for 3-D flood hazard maps in urban areas: new opportunities and perspectives. **2020**:1364–8152. Available from: https://doi.org/10.1016/j.envsoft.2020.104889

[54] Tingitana L 2018 Marginalized communities are taking to the skies to secure their way of life *https://storymaps.arcgis.com/stories/d0e723e02b594d209a11a9c0747d0ffb*

[55] E Sepasgozar S M 2021 Buildings differentiating Digital Twin from Digital Shadow: Elucidating a Paradigm Shift to Expedite a Smart, Sustainable Built Environment. *https://doi.org/10.3390/buildings11040151*

[56] ABI Research 2019 Transformative Urban Digital Twin and City Modeling Deployments to exceed 500 by 2025 *Available from: https://www.abiresearch.com/press/transformative urban-digital-twin-and-city-modeling-deployments-exceed-500-2025/*

[57] National Research Foundation 2021 https://www.nrf.gov.sg/programmes/virtual-singapore *Available from: https://www.nrf.gov.sg/programmes/virtual-singapore*

[58] Diarte J, Bang S H, Ventrella J, Burleson G, Machado M and Obonyo E 2020 Resilient Affordable Housing for Flood Risk Reduction: A Review of Interventions in Four Cities in East Africa. *Available from: https://www.engineeringforchange.org*

[59] Liu S, Brewster C and Shaw D 2013 Ontologies for Crisis Management: A review of State of the Art in Ontology Design and Usability *Available from: http://www.macs.hw.ac.uk/*~yjc32/project/ref-emergency response/ontology-crisis-mgmt Liu_ISCRAM13.pdf

[60] Ye X, Wang S, Lu Z, Song Y and Yu S. Towards an AI-driven framework for multi-scale urban flood resilience planning and design. *Comput Urban Sci.* Dec;**1**(1)

Acknowledgement

This research is supported by the National Science Foundation (Award Number 2019754) through the Belmont Forum Collaborative Research Action project: Advancing the Resilience of Low-Income Housing through Climate Science and Data Analytics.