Nguyen, T.D., Zeng, Q., and Pishdad, P. (2025). Integrating Construction 4.0 Technologies to strengthen Post-Disaster Construction Supply Chain. *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction* (IGLC33) (pp. 705-716). https://doi.org/10.24928/2025/0204

INTEGRATING CONSTRUCTION 4.0 TECHNOLOGIES TO STRENGTHEN POST-DISASTER CONSTRUCTION SUPPLY CHAIN

Tran Duong Nguyen[1], **Qinghao Zeng**[2], and **Pardis Pishdad**[3]

ABSTRACT

Natural or artificial disasters, such as earthquakes, pandemics, conflicts, and hurricanes, often lead to the displacement of people, damage to critical infrastructure, and disruption of the supply chain. Rapid and resilient post-disaster reconstruction is thus essential for communities to recover faster. This paper proposes a framework for integrating emerging technologies, including Building Information Modeling (BIM), Reality Capture, AI, Computer Vision, GPS/GIS, Construction 3D Printing (C3DP), and Modular Construction (MC), with Lean Construction (LC) principles to streamline and strengthen the post-disaster reconstruction supply chain. This paper identifies the common challenges in post-disaster reconstruction through a literature review, investigates technology-driven solutions, and proposes strategies to strengthen the reconstruction supply chain regarding speed and resilience. The integrated framework addresses four specific reconstruction phases, from rapid damage assessment and data management to planning, design, and on-site implementation. Our findings emphasize the importance of cross-sector collaboration, specialized training, and strategic investment in these technologies to improve disaster response, recovery, and long-term community resilience. Additionally, this paper provides recommendations for policymakers, practitioners, and stakeholders, highlighting how advanced technologies could reduce timelines, lower costs, and ensure a more sustainable and adaptive rebuilding process in the face of future disruptions.

KEYWORDS

Post-disaster Reconstruction, Emerging technologies, Construction 4.0, Construction Supply chain, Sustainable Recovery Strategies.

INTRODUCTION

Various disastrous events have threatened communities and infrastructures worldwide, including natural calamities such as earthquakes, floods, pandemics, geopolitical conflicts, and wars. In September 2017, Hurricane Maria, a devastating Category 5 storm damaged wide parts of the island of Puerto Rico and caused approximately 130,000 people to lose their homes, according to Junod et al. (2022). These factors were further exaggerated by the ravaging of the entire infrastructure on that island, where the hurricane ravaged its electric grid, further complicating a dismal displacement situation marked by destroyed road infrastructure and water supplies. The earthquake in the border region of Turkey and Syria made immense communities lose their homes, and people lost their lives. It was reported that a magnitude 7.8

[1] Ph.D. Student, Georgia Institute of Technology, Atlanta, Georgia, United States, dnguyen458@gatech.edu, https://bc.gatech.edu/people/tran-nguyen, orcid.org/0000-0002-0024-4828

[2] Ph.D. Student, Georgia Institute of Technology, Atlanta, Georgia, United States, qzeng41@gatech.edu, orcid.org/0000-0002-4313-6800

[3] Ph.D., Full Professor, Georgia Institute of Technology, Atlanta, Georgia, United States, pardis.pishdad@design.gatech.edu, https://bc.gatech.edu/people/pardis-pishdad, orcid.org/0000-0003-4208-9755

earthquake damaged many buildings. Such destruction displaced families from their homes and was likely to deprive them of the most indispensable services. As reported by OCHA (2023), at least 230,000 buildings across 11 provinces in Turkey were either damaged or destroyed, and at least 10,600 buildings have been entirely or partially destroyed in Northwest Syria. For instance, in Aleppo, Syria, around 3,500 buildings are damaged and require structural repair, while 700 buildings are categorized as unsafe per OCHA (2023a) reports. The ongoing conflict in the region further exacerbates the crisis, making access to and delivery of aid particularly challenging.

Beyond the immediate devastation of disasters, a critical challenge in reconstruction is the severe disruption to the construction supply chain. Limited material availability, logistical bottlenecks, and workforce shortages often delay recovery efforts, leading to extended displacement periods for affected communities (Liu et al., 2024). In the wake of Hurricane Maria (2017) and the Turkey-Syria earthquake (2023), material procurement and distribution delays significantly slowed reconstruction efforts. The fragmented nature of traditional construction supply chains and inefficient stakeholder coordination exacerbate these issues. A more digitally integrated and automated supply chain is essential to improving responsiveness and resilience.

To enhance supply chain resilience, the concept of Construction 4.0 (C4.0) has emerged as an approach to construction that leverages advanced technologies, such as BIM, Reality Capture, Geographic Information System (GIS), Computer Vision, AI, C3DP, and Modular Construction (MC), to improve efficiency, productivity, quality, and sustainability. It is conceptualized upon Industry 4.0, described by Hossain and Nadeem (2019), based on a fourth industrial revolution characterized primarily by the application of cyber-physical systems, which are the bidirectional interaction of systems in cyberspace and physical space. C4.0 technologies can transform post-disaster reconstruction by enhancing supply chain resilience and efficiency. Emerging technologies such as Blockchain for transparent procurement, AI for predictive demand forecasting, and Internet of Things (IoT)-enabled materials tracking can significantly enhance supply chain resilience (Sawhney et al., 2020). Technologies such as AI-driven predictive analytics can forecast material demand based on disaster impact assessments, reducing procurement delays. Similarly, blockchain-based smart contracts can enhance transparency and automate procurement processes, ensuring the timely delivery of essential supplies. Integrating these technologies into the reconstruction supply chain can enable faster response times, reduced waste, and improved stakeholder coordination.

Despite the increasing adoption of C4.0 technologies, limited research has explored their role in optimizing post-disaster reconstruction supply chains. Existing studies focus on individual technological applications, such as BIM for design optimization or AI for damage assessment, without addressing their integrated impact on supply chain resilience. (Rawat et al., 2024). Moreover, the intersection of LC principles with C4.0 in disaster recovery supply chains remains underexplored. This study bridges the gap by proposing an integrated framework that leverages C4.0 technologies to enhance the agility, transparency, and sustainability of the post-disaster construction supply chain.

Based on these observations, this research will investigate integrating C4.0 technologies with LC principles in strengthening post-disaster reconstruction supply chains. Specifically, the research goals are to (1) explore how C4.0 technologies, when paired with lean methods, could reduce reconstruction time and waste; (2) assess how these combined approaches could enhance project coordination, quality control, and overall resilience; and (3) provide policy recommendations and actionable strategies for stakeholders to implement these potential solutions in diverse post-disaster contexts. The study's significance lies in addressing a critical gap in how C4.0 technologies and lean concepts could be synergized to optimize post-disaster reconstruction processes while ensuring long-term sustainability and community resilience.

LITERATURE REVIEW

Construction 4.0 (C4.0) represents the construction industry's digital transformation, incorporating advanced technologies like BIM, Reality Capture, and AI. It constitutes a paradigmatic change that underpins efficiency, sustainability, and resilience, using real-time data, automation, and smart decision-making processes across the entire construction lifecycle. (Sawhney et al., 2020). Despite the rapid development of individual C4.0 tools, their integrated role in enhancing post-disaster construction supply chains has not been sufficiently studied. The current literature treats BIM, AI, or MC as isolated solutions, with limited attention to their combined effect on supply chain resilience and coordination in post-disaster contexts. Throughout the current literature, three ideas are mainly discussed which are (1) using a GPS or GIS system to locate, track, and monitor the disaster status, (2) adopting MC for temporary post-disaster shelter construction, (3) applying AI algorithms to optimize resource allocation, and (4) BIM for cost estimation and virtual planning. Here is a table summarizing some of the primary problems identified in the literature and outlining the technology-driven solutions proposed by various researchers.

Table 1: Summarization of the problems and potential solutions in literature

Problems	Potential solutions	Sources
Damage estimation and area location identification	GPS or GIS sensor network	(John Samuel Raj K et al., 2016)
Manage historical data	Integrated historical database management system	(Bahmani & Zhang, 2022)
Temporary post-disaster shelter design and material selection	Material recovery, reuse, and transformation	(Opdyke et al. 2016)
Urban Rehabilitation and Reconstruction Difficulties	Establish a planning support system.	(Bahmani & Zhang, 2022)
Need a quick and immediate solution to post-disaster housing problems	Modular Offsite Construction for Emergency Situations	(Shahzad et al., 2022)
Mismanagements	ICT-based methods	(Shuvo et al., 2022)
Limited resources for shelter building	A K-Nearest Neighbor (KNN) model was used to assist decision-makers in selecting suitable temporary housing.	(Afkhamiaghda & Elwakil, 2021)
Status monitoring during a disaster	Remote sensing could monitor the loss of housing and agricultural facilities in a tornado disaster.	(Cui et al., 2020)
Simulation of the reconstruction process	Using Python to help decision-making during the reconstruction process	(Huling & Miles, 2015)
Identify the Feasibility of Reconstruction Alternatives	Cost estimation using BIM	(Kermanshachi & Rouhanizadeh, 2018)
Improve the efficiency of obtaining the construction permit in post-disaster recovery.	BIM-based Virtual Permitting Framework (VPF)	(Messaoudi & Nawari, 2020)
BIM to support rapid recovery and rebuilding.	Building Information Modelling (BIM)	(Drogemuller, 2015)
Post-disaster building damage detection using pre-event imagery	Anomaly Detecting Generative Adversarial Network (ADGAN)	(Tilon et al., 2020)
To detect post-disaster damages from remote sensing imagery	Three texture analyses, Gabor filters, Local Binary Pattern, and Histogram of Oriented Gradients, were applied to UAV mosaic images	(Ghaffarian et al., 2019)
Compare costs: C3DP vs. conventional temporary housing	Financial Analysis	(Gregory et al., 2016)
Two-stage stochastic C3DP knapsack problem	Linear Integer Programming	(Tönissen & Schlicher, 2021)

However, limited research connects these technologies directly to supply chain management challenges such as material delivery delays, coordination breakdowns, and inventory inefficiencies. In post-disaster reconstruction, the supply chain becomes a critical bottleneck. Issues such as damaged infrastructure, unpredictable demand, and the urgency of deployment require a resilient and responsive system.

SUPPLY CHAIN MANAGEMENT IN POST-DISASTER RECONSTRUCTION

Supply chain management is pivotal in coordinating material procurement, logistics, and workforce mobilization for reconstruction efforts. Disasters often severely disrupt these processes, leading to material shortages, delivery delays, and misaligned workflows (Bahmani & Zhang, 2022). Traditional construction supply chains are fragmented and lack the real-time responsiveness necessary for post-disaster contexts. C4.0 technologies have the potential to modernize and digitalize post-disaster supply chains. For example, blockchain can increase transparency and security in procurement; IoT can enable real-time material tracking, and AI can forecast material needs and delivery windows based on dynamic site conditions. When combined, these tools enable data-driven supply chain management that is more agile and resilient to disruptions (Sawhney et al., 2020).

INTEGRATING LEAN CONSTRUCTION WITH C4.0 IN POST-DISASTER CONTEXT

Lean Construction is focusing on waste minimization, flow efficiency, and continuous improvement, offers synergistic value when applied alongside C4.0 tools in post-disaster reconstruction. (Mojtahedi & Oo, 2012; Syaputra & Rarasati, 2023). Specific Lean tools and principles enhance the functionality of digital technologies: (1) Value Stream Mapping (VSM): Identifies bottlenecks in logistics and supports AI-driven process optimization; (2) Just-in-Time (JIT): Enables efficient inventory and delivery coordination, especially when integrated with MC and digital logistics platforms; (3) 5S (Sort-Set in order-Shine-Standardize-Sustain) and Visual Management: Improve site-level material handling and align well with IoT-enabled workflows. This is evident in Shahzad et al. (2022) who demonstrate how MC, supported by LC and C4.0, significantly reduces build time and material waste during emergency housing deployment. Likewise, Moghadam & Al-Hussein (2013) show how VSM can be applied to BIM-based workflows to streamline coordination and material flow.

USAGE OF A GPS OR GIS SYSTEM

Since natural disasters are unpredictable, damage estimation is significant for quick recovery and relief. Based on the research of John Samuel Raj K et al. (2016)The most achievable idea for damage estimation is evaluating the position difference for GPS units, usually inside buildings. A GIS is one of the standard tools for storing, analyzing, and visualizing the geographical data provided by GPS systems. Merging these two systems can help evaluate buildings' disaster status and damage situations.

Data storage and structuring are significant issues if GPS or GIS systems are utilized, and for learning from previous historical cases, as stated in the research by Bahmani and Zhang (2022). This research is valuable as it aims to provide a conceptual framework for establishing an experience-based database to manage the following disasters from a continuous building lifecycle perspective. Besides the issues with data, problems also exist during data transmission, including the lengthy risk assessment using ancient data generation processes and the lack of accessibility and report-based data products (Shuvo, Islam, & Islam, 2022). Hence, a GIS system could make the data transmission process more efficient, transparent, and convenient. Besides, LC principles can enhance GIS in disaster management by streamlining data collection and eliminating redundancies, ensuring only relevant, accurate information is processed and shared for timely decision-making during disaster response and recovery.

ADOPTION OF MODULAR CONSTRUCTION (MC)

With the benefits of standardization and more convenience for transportation, MC has recently gained rapid market acceptance. (Lee & Lee, 2021). Natural disasters require a quick and immediate solution for temporary housing construction, which is usually time-consuming and waste-producing. However, if we adopt shelters using MC for post-disaster temporary housing construction, these two problems could be solved since MC has the potential to enhance the whole process due to its intrinsic features of time efficiency (Shahzad et al., 2022). With LC principles, MC can enhance efficiency by minimizing material waste, optimizing transportation logistics, and standardizing workflows (Shahzad et al., 2022).

APPLY AI FOR OPTIMIZATION

Due to the multi-objective nature of post-disaster temporary housing establishment, the optimized model for estimating housing demand is complicated. That is why an ordinal classification framework is introduced using the K-Nearest Neighbour (KNN) model from the research by Afkhamiaghda & Elwakil (2021) To help decision-makers choose the right type of temporary houses based on their needs. This model could also inform the factors affecting the post-disaster temporary housing process in terms of construction delivery method, market prices, material types, and demands. Another article presents a home reconstruction simulation process using Python to support decision-making. (Huling & Miles, 2015). Reconstruction simulation involves recovering over 1,300 households to increase the accuracy of the results. LC enhances AI-driven optimization by embedding continuous feedback loops into machine learning models that assure improvement at all reconstruction steps.

VISUAL IMAGING

To proceed with a disaster recovery plan, it is necessary to gauge the extent of damage, prepare accordingly, and allocate resources. Remote sensing is employed to obtain post-disaster event mosaic Unmanned Aerial Vehicle (UAV) images, and the texture analysis frameworks are tested. The histogram of the Oriented Gradients was revealed to have more potential than the Local Binary Pattern and Gabor Filters in debris identification (Ghaffarian et al., 2019). A disaster recovery plan can save time, money, and lives before a disaster hits. Anomaly Detecting Generative Adversarial Network (ADGAN) is a ground-breaking technology powered by deep learning networks that only requires pre-event imagery of buildings in their undamaged state to assess the post-event damage scale (Tilon et al., 2020). This information can be utilized to prepare a disaster recovery plan in the pre-event phase.

BUILDING INFORMATION MODELING (BIM)

These natural calamities badly ruin resources, both buildings and human lives. Since it is impossible to put a dollar price on human lives, reconstruction after disasters involves prudent financial allocations. BIM-based cost estimation allows performance quantity take-offs relative to multiple projects and provides the best alternative to proceed with based on real-time cost updates, and it can be leveraged to develop cost estimation APIs (Kermanshachi & Rouhanizadeh, 2018). Cost and time are essential constraints when rebuilding after disasters. The construction permitting process is one critical factor that needs to be addressed to speed up the process. Messaoudi & Nawari (2020) introduces a Virtual Permitting Framework addressing present issues using BIM-based automated code compliance checks (Drogemuller, 2015) This study finds how effective BIM data can be utilized to make infrastructure disaster-resilient and how geospatial data can be helpful in post-disaster recovery.

CONSTRUCTION 3D PRINTING (C3DP)

The most attractive quality of C3DP is its ability to deploy and speed up infrastructure. However, it also comes with a high cost, limited availability, and colossal size. To address this, a two-stage stochastic knapsack problem is created to check whether it is beneficial to bring 3D printers, and by how much, to a disaster area, and solved using linear programming (Tönissen & Schlicher, 2021). One of the significant downfalls of C3DP is that it is costly. Utilizing 3D Printers, when compared to traditional temporary houses such as bamboo, timber frame, steel frame, and precast structures, has proven to be well within the range of conventional temporary housing (Gregory et al., 2016).

METHODOLOGY

Collecting data from industry and research-related fields in post-disaster reconstruction is essential to gain a complete knowledge of the topic, including practical insights and theoretical understanding. This study applied qualitative research methodology to identify the problem, perform a literature review, analyze data, collect examples, and write a research paper. This methodology addressed the potential use case of integrating advanced technologies for efficient and effective post-disaster reconstruction in a research paper. This further helps draw on valuable lessons from the challenges and opportunities of using advanced technologies for post-disaster reconstruction that might be useful to inform policymakers, practitioners, and stakeholders to make informed decisions.

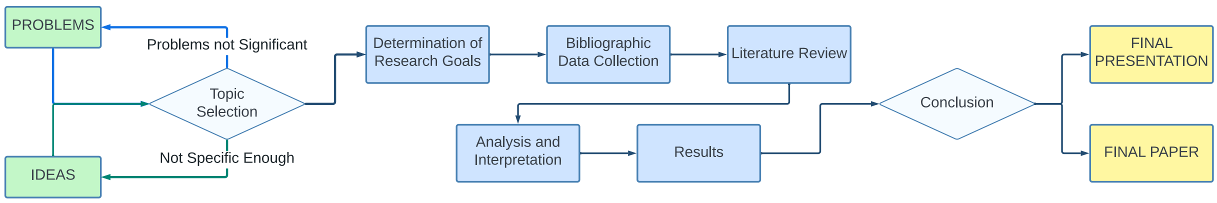

Figure 1: Research Methodology Process

The systematic literature review was conducted using a structured and transparent process guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. Key academic databases, including Google Scholar, Scopus, Web of Science, and ScienceDirect, were searched. The keywords used included combinations of terms such as *"Construction 4.0," "post-disaster reconstruction," "supply chain resilience," "Lean Construction," "BIM," "AI in construction,"* and *"modular housing*." Articles published between 2013 and 2023 were considered to ensure relevance and quality. Only peer-reviewed journal and conference papers were included if they focused on emerging construction technologies, Lean principles, or supply chain challenges in post-disaster scenarios. Irrelevant, duplicate, or non-empirical studies were excluded. The initial literature review identified research gaps and emerging trends in the construction industry's relevant post-disaster reconstruction topics. This step helped the researchers become familiar with the current state of knowledge and the challenges the construction industry faces in post-disaster reconstruction.

Following the initial screening, the selected literature was analyzed thematically. The detailed literature review attempted to answer the following research questions: (1) What is the current state of applying emerging technology for post-disaster recovery in research-related fields? (2) How can emerging technologies be integrated with post-disaster reconstruction projects? (3) How can using advanced technologies in post-disaster reconstruction impact the sustainability and resilience of buildings and communities? (4) What challenges and opportunities are associated with implementing advanced technologies in post-disaster reconstruction projects, and how can these challenges be overcome? LC principles further examined these questions, assessing how they could address inefficiencies and promote sustainable outcomes.

Lastly, the review revealed a significant lack of integrated models that combine C4.0 tech.

and LC to address supply chain inefficiencies in post-disaster contexts. While several studies explored these approaches separately, few addressed their combined potential to enhance speed, coordination, and sustainability in reconstruction efforts. Based on the insights, a conceptual framework was developed. It maps how digital technologies, and Lean practices can work together across four key phases of post-disaster recovery: assessment, data management, planning and design, and on-site implementation. This model supports decision-making among practitioners, policymakers, and researchers, offering a clear pathway to build a more resilient and agile post-disaster construction supply chain.

RESULTS, DISCUSSIONS, AND RECOMMENDATIONS

RESULTS & DISCUSSIONS

Natural and artificial disasters can cause massive destruction to buildings, utilities, and public infrastructure, leaving communities without shelter, electric power, and running potable water. Effective post-disaster reconstruction requires speed and coordination across fragmented construction supply chains. This study examined how emerging technologies under the umbrella of C4.0, combined with LC principles, can improve the resilience and responsiveness of these supply chains. The findings highlight that incorporating Lean practices into every stage of the reconstruction framework, from assessment to implementation, enhances the benefits of advanced technologies. For instance, using value stream mapping during the assessment phase helps reduce delays, while just-in-time material delivery complements MC effectively (Moghadam & Al-Hussein, 2013).

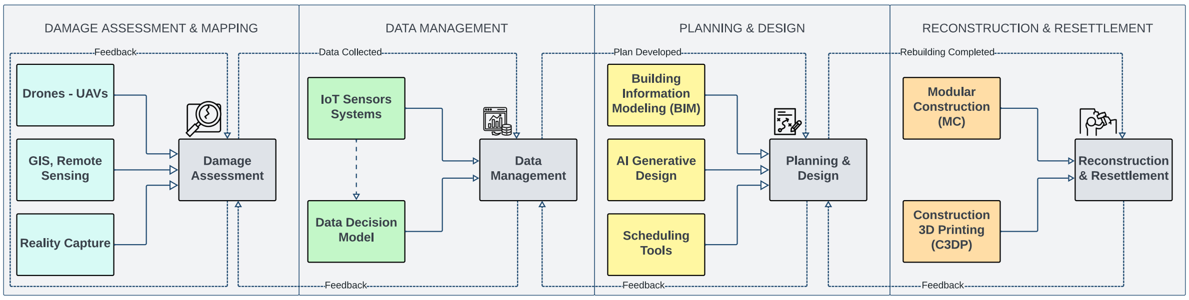

Figure 2: Proposal of a conceptual framework for post-disaster reconstruction

This diagram presents a four-phase framework integrating advanced technologies and LC. It begins with damage assessment using drones, GIS, and reality capture, then data management through IoT sensors and decision models. BIM, AI Generative tools, and scheduling systems support planning and design, leading to rapid reconstruction using modular construction and C3DP. Feedback loops in each phase ensure continuous improvement, coordination, and efficiency throughout recovery.

ASSESSMENT AND MAPPING

The first step in post-disaster reconstruction is to assess the extent of the damage to existing physical buildings, utilities, and other environments in the affected area. UAVs and drones can collect data on the area using laser scanning technology quickly and efficiently. This innovative technology will provide accurate 3D models of the affected area and further assist respondents in identifying damaged buildings and other infrastructure without wasting time. Computer vision also helps identify structural damage to buildings and public infrastructure, further streamlining the assessment procedure. Implementing Lean principles at this stage ensures that only critical damage zones are focused upon and unnecessary data collection is avoided. The collected data can further be used to analyze the best reconstruction method. This can include identifying which buildings and infrastructure are top priorities for repair or replacement and optimizing the reconstruction process to reduce waste and increase efficiency.

The mentioned technologies would be used by a separate team that would have the credibility to drive UAVs and the operation of drones, along with the tech team who are acquainted with laser scanning technology and Computer Vision. The on-field engineers most use these technologies. As drones can better survey work, 60-70% of the work it takes compared to the traditional methods of obtaining survey data, we can see drones in the construction industry have also grown 239% annually, according to the article by (JOUAV, 2022).

DATA MANAGEMENT

The data collected during the mapping and assessment phase can be managed and analyzed to provide valuable insights for the reconstruction process. Advanced analytics tools can then determine the best and most economical reconstruction methods based on variables regarding materials availability, labor resources, and available transport methods. Predictive analytics tools, for example, can identify what the material needs would be for a reconstruction process, whereby responders can preload and pre-position supplies for the affected area. Supply chain management systems can also ensure that materials arrive at the right place and time, making the reconstruction process even more effective. Decision models, on the other hand, may allow you to make decisions effectively. Lean-driven workflows can further enhance data management by streamlining processes, reducing waste in material handling, and aligning logistics to real-time requirements.

A third-party data analytics team would manage assessment and mapping data to coordinate supply chain management and serve as an integrated communication channel among project stakeholders. Integrated data management frameworks have been proposed to facilitate stakeholder coordination and decision-making throughout the recovery lifecycle (Bahmani & Zhang, 2022).

PLANNING AND DESIGN

Once the data has been collected and analyzed, detailed plans and designs for reconstruction can be created. BIM software can create digital models of the affected area, incorporating data from the mapping and assessment phase to accurately represent the area's current state. Generative design can create multiple design options for the reconstruction process, allowing responders to compare different options and select the most efficient and effective solution quickly and easily. This method can include selecting the most appropriate building materials, design layouts, and other factors impacting the reconstruction process. LC, such as pull-based planning and collaborative design, ensures project milestones align with community priorities and resource availability.

Architects, VDC (Virtual Design and Construction), and Project Managers will benefit from the project with the help of technologies like BIM, Generative Design, and Generative Scheduling, which would help fast-track the pre-reconstruction process much more efficiently. As we have seen recently, the application of BIM within the AEC industry has increased drastically. The latest forecast also shows that BIM will continue with the double-digit growth of Compound Annual Growth Rate (CAGR) of 11.2% by 2026 (*Markets*, 2022).

CONSTRUCTION AND RESETTLEMENT

The final step of this post-disaster reconstruction process involves rebuilding and implementing the digital models created during the planning and design. C3DP and MC methods could fast-track the construction process in newly constructed buildings and infrastructures, enabling faster and better reconstruction. MC builds parts in a factory setting and assembles them on-site for faster construction and less material waste. With C3DP, building components can be customized and fabricated rapidly to expedite construction processes further. Once the new buildings and infrastructure have been built, ensuring they are supplied with the resources to sustain the communities affected becomes even more critical. Supply them with clean drinking water, electric power, heating and cooling, and other essentials.

Consequently, integrating advanced technologies can provide a rapid and effective post-disaster reconstruction response. By leveraging these technologies, responders can quickly and efficiently assess the damage, manage data, plan, design, and rebuild, and implement new buildings and infrastructure. Aligning these technologies with Lean principles ensures that reconstruction efforts achieve speed, cost-effectiveness, long-term sustainability, and resilience. Fabricators using technologies like C3DP and MC working off-site will speed up the construction projects with very few errors in place. Superintendents and field engineers will benefit from these technologies as they will provide an opportunity to shift away from traditional construction to manufacturing off-site. It is also known that these technologies will also indirectly implement lean principles, reducing materials' wastage. The above-proposed framework is a better solution, as it embeds emerging technologies within each section. Economically, they can bring more efficiency to the process, improve safety in assessment and construction, better implement sustainability features, and enhance collaboration for better cost savings and productivity with an improved project outcome.

RECOMMENDATIONS

Among others, policymakers, practitioners, local agencies, international agencies, and other stakeholders must consider several factors if C4.0 technologies and lean principles are to be successfully deployed. First, stakeholders must assume a lean mindset focusing on value creation, waste reduction, and continuous improvement in the reconstruction lifecycle. They must also ensure that sufficient investment is secured for research and development to support the continued evolution of these technologies. Second, they must put teams of designers, engineers, builders, safety professionals, and other specialists ready to respond promptly and effectively after disasters. Lean-driven collaborative planning ensures that these teams work cohesively, avoiding silos and improving communication. Table 2 provides a comparative analysis of various disaster assessment methodologies that highlighting their key features, advantages, and limitations to support informed decision-making in post-disaster recovery efforts. This effort also requires decision-makers to address the skills gap in the construction industry since many of these technologies require specialized skills and knowledge, and it is essential to ensure a sufficient pool of qualified workers to implement them. Last, they must ensure that there is adequate technological infrastructure in place to support these applications. It also includes high-speed internet connectivity, access to cloud-based computing resources, and the availability of C3DP facilities.

CONCLUSIONS AND FURTHER RESEARCH

The construction industry is at a strategic turning point where technology-based and process-driven approaches are essential to address the complexities of post-disaster reconstruction. The increasing frequency and severity of natural and human-made disasters have revealed critical gaps in traditional reconstruction methods, particularly in supply chain responsiveness, coordination, and resource optimization.

The study contributes to the body of knowledge by providing a novel integration of C4.0 technologies with LC principles to strengthen the post-disaster reconstruction supply chain. A conceptual framework was developed based on a systematic literature review and structured thematic analysis, demonstrating how advanced technologies, such as BIM, AI, GIS, IoT, and MC, can be strategically deployed across four phases of disaster recovery: assessment, data management, planning, and implementation. Unlike prior studies that examine technologies or Lean practices in isolation, this research bridges a critical gap by synthesizing them into a unified framework tailored to the unique demands of post-disaster contexts. This positions the framework as a distinct contribution to disaster resilience, supply chain management, and construction innovation. From the findings, it is important to note the need to equip stakeholders with the necessary training in Lean practices and provide a robust technological infrastructure to accommodate these integrations. By fostering collaboration and technical capabilities, the construction industry would be able to respond to pressing demands for adaptive, responsive, and resource-efficient reconstruction strategies.

Table 2: Potential of C4.0 Technologies Combined with LC for Post-Disaster Efforts

C4.0 Technologies	Potential benefits combined with Lean Principles
Building Information Modeling (BIM)	Creates 3D models with building geometry and data to boost collaboration and reduce errors (*Autodesk*, 2021). Lean tools like value stream mapping enhance BIM by removing workflow inefficiencies (Moghadam & Al-Hussein, 2013).
Reality Capture	Scans from lasers, photogrammetry, or drones (Drone Deploy, 2022) provide precise points for detailed planning, improving stakeholder coordination, and reducing waste. Lean focuses on data capture in key areas to minimize rework.
Geographic Information Systems (GIS)	Collects and analyzes geospatial data to represent site conditions and impacts (John Samuel Raj K et al., 2016), while Lean workflows enhance GIS use for efficient resource allocation and decisions.
Computer Vision (CV)	Automates defect detection and progress monitoring (Ghaffarian et al., 2019); with Lean, it reduces rework and supports continuous improvement.
Artificial Intelligence (AI)	Analyzes sensor data to predict building behavior, automate tasks, and cut time and costs (Afkhamiaghda & Elwakil, 2021). AI also optimizes material delivery, lowering inventory costs and congestion. Pull planning with AI aligns resources to project milestones.
Construction 3D Printing (C3DP)	Creates building components from digital models, minimizing material waste and speeding up timelines (Ngo et al., 2018). Lean principles reduce material wastage further by aligning designs with demand-driven workflows.
Modular Construction (MC)	Pre-build structures off-site for faster, cost-effective assembly with improved quality (Shahzad et al., 2022). Lean principles support MC through standardization and optimized workflow.

Further studies need to be done in the future to quantify the impacts brought about by the integration of Lean principles with C4.0 technologies based on key performance indicators: carbon footprint reduction, cost savings, and project completion times. Besides, community engagement should be given more attention within the lean workflows to ensure alignment of reconstruction efforts with the needs and priorities of the local community. These will create meaningful change at the policy, practitioner, and research levels in post-disaster reconstruction toward sustainable, more efficient, sustainable, and efficient outcomes. Integrating LC and C4.0 technologies provides a promising pathway to build back better in the face of future disasters, creating sustainable and liveable environments for future generations.

REFERENCES

Afkhamiaghda, M., & Elwakil, E. (2021). The Application of Supervised Classification Techniques in Selecting the Most Optimized Temporary House Type in Post-disaster Situations. *2021 IEEE Conference on Technologies for Sustainability (SusTech)*, 1–6. https://doi.org/10.1109/SusTech51236.2021.9467421

Autodesk. (2021). *What Is BIM | Building Information Modeling | Autodesk*. https://www.autodesk.com/solutions/aec/bim

Bahmani, H., & Zhang, W. (2022). A conceptual framework for the integrated management of disaster recovery projects. *Natural Hazards: Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, *113*(2), 859–885.

Cui, Y., Liu, M., & Li, S. (2020). Emergency monitoring and post-disaster reconstruction monitoring in the tornado disaster in Yancheng, Jiangsu. *MIPPR 2019: Remote Sensing Image Processing, Geographic Information Systems, and Other Applications*, 131. https://doi.org/10.1117/12.2538181

Drogemuller, R. (2015). *BIM support for disaster response*. *Risk-Informed Disaster Management: Planning for Response, Recovery and Resilience*, 391-405.

DroneDeploy. (2022). *What is Reality Capture and Why Should You Invest in it?* https://www.dronedeploy.com/blog/what-is-reality-capture-and-why-should-you-invest-in-it

Ghaffarian, S., Kerle, N., Pasolli, E., & Jokar Arsanjani, J. (2019). Post-Disaster Building Database Updating Using Automated Deep Learning: An Integration of Pre-Disaster OpenStreetMap and Multi-Temporal Satellite Data. *Remote Sensing*, *11*(20), Article 20. https://doi.org/10.3390/rs11202427

Gregory, M., Hameedaldeen, S. A., Intumu, L. M., Spakousky, J. J., Toms, J. B., & Steenhuis, H. J. (2016). 3D printing and disaster shelter costs. *2016 Portland International Conference on Management of Engineering and Technology (PICMET)*, 712–720. https://doi.org/10.1109/PICMET.2016.7806594

Hossain, M. A., & Nadeem, A. (2019). Towards Digitizing the Construction Industry: State of the Art of Construction 4.0. *Proceedings of International Structural Engineering and Construction*, *6*(1). https://doi.org/10.14455/ISEC.res.2019.184

Huling, D., & Miles, S. B. (2015). Simulating disaster recovery as discrete event processes using Python. *2015 IEEE Global Humanitarian Technology Conference (GHTC)*, 248–253. https://doi.org/10.1109/GHTC.2015.7343980

Raj, J. S. K., Thapa, N. K., & Balakrishnan, R. (2016). Post-disaster damage estimation using an integrated GPS sensor network and GIS. *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, 1234–1238. https://doi.org/10.1109/WiSPNET.2016.7566333

JOUAV. (2022). *Drone in Construction & Infrastructure: Benefits, Uses, and Case Studies*. JOUAV. https://www.jouav.com/industry/drone-in-construction

Junod, A. N., Morales-Burnett, J., & Rivera, F. (2022). *Five Lessons from the Aftermath of Hurricane Maria for Communities Preparing for Climate Migration*. Urban Institute. https://www.urban.org/urban-wire/five-lessons-aftermath-hurricane-maria-communities-preparing-climate-migration

Kermanshachi, S., & Rouhanizadeh, B. (2018). Feasibility Analysis of Post-Disaster Reconstruction Alternatives Using Automated BIM-Based Construction Cost Estimation Tool. *Canadian Society for Civil Engineering (CSCE) 6th International Disaster Mitigation Specialty Conference*. https://www.Semanticscholar.Org/Paper/Feasibility-Analysis-Of-Post-Disaster-Alternatives-Kermanshachi-Rouhanizadeh/9d18680255ff77a7fcac802e646f4969cf836ed5

Lee, D., & Lee, S. (2021). Digital Twin for Supply Chain Coordination in Modular Construction. *Applied Sciences*, *11*(13), Article 13. https://doi.org/10.3390/app11135909

Liu, K., Chang-Richards, A., Costello, S. B., L'Hermitte, C., & Li, N. (2024). What factors influence building material supply for post-disaster reconstruction and recovery? A systematic review applying systems thinking. *International Journal of Disaster Risk Reduction*, *114*, 104981.https://doi.org/10.1016/j.ijdrr.2024.104981

Markets Research (2022). *BIM Software Global Market Report 2022: Continuously Increasing Functionality and New Features Boosting Adoption*. GlobeNewswire Newsroom.

https://www.globenewswire.com/en/news-release/2022/11/14/2554604/28124/en/BIM-Software-Global-Market-Report-2022-Continuously-Increasing-Functionality-and-New-Features-Boosting-Adoption.html

Messaoudi, M., & Nawari, N. O. (2020). BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida. *International Journal of Disaster Risk Reduction*, *42*, 101349. https://doi.org/10.1016/j.ijdrr.2019.101349

Moghadam, M., & Al-Hussein, M. (2013). *Resource Optimization for Modular Construction Through Value Stream Map Improvement*. *Proceedings of the 21st Annual Conference of the International Group for Lean Construction (IGLC 21).* 503–512. https://iglc.net/Papers/Details/931

Mojtahedi, S. M. H., & Oo, B. L. (2012). Possibility Of Applying Lean in Post-Disaster Reconstruction: An Evaluation Study. *Proceedings of the 20th Annual Conference of the International Group for Lean Construction*.

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

OCHA. (2023, March 9). *Türkiye: 2023 Earthquakes Situation Report No. 8, As of 9 March 2023 - Türkiye | ReliefWeb*. https://reliefweb.int/report/turkiye/turkiye-2023-earthquakes-situation-report-no-8-9-march-2023

Opdyke, A., Javernick-Will, A. N., Koschmann, M., & Moench, M. (2016). *Characterizing Post-Disaster Shelter Design and Material Selection: Lessons from Typhoon Yolanda in the Philippines | Global Projects and Organizations Research Group | University of Colorado Boulder*. https://www.colorado.edu/lab/gpo/2016/05/24/characterizing-post-disaster-shelter-design-and-material-selection-lessons-typhoon

Rawat, A., Witt, E., Roumyeh, M., & Lill, I. (2024). Advanced Digital Technologies in the Post-Disaster Reconstruction Process- A Review Leveraging Small Language Models. *Buildings*, *14*(11), Article 11. https://doi.org/10.3390/buildings14113367

Sawhney, A., Riley, M., & Irizarry, J. (Eds.). (2020). *Construction 4.0: An Innovation Platform for the Built Environment*. Routledge. https://doi.org/10.1201/9780429398100

Shahzad, W. M., Rajakannu, G., & Kordestani Ghalenoei, N. (2022). Potential of Modular Offsite Construction for Emergency Situations: A New Zealand Study. *Buildings*, *12*(11), Article 11. https://doi.org/10.3390/buildings12111970

Shuvo, A. A. M., Islam, M. T., & Islam, M. R. (2022). *Role of information and communication technologies in Build Back Better to post-disaster recovery practices: Insights from Bangladesh*. CoLab. https://colab.ws/articles/10.1108%2Fijdrbe-08-2021-0097

Syaputra, T. A., & Rarasati, A. D. (2023). A conceptual framework for implementing lean construction and building information modeling (BIM) in post-disaster housing reconstruction projects. *IOP Conference Series: Earth and Environmental Science*, *1173*(1), 012065. https://doi.org/10.1088/1755-1315/1173/1/012065

Tilon, S., Nex, F., Kerle, N., & Vosselman, G. (2020). Post-Disaster Building Damage Detection from Earth Observation Imagery Using Unsupervised and Transferable Anomaly Detecting Generative Adversarial Networks. *Remote Sensing*, *12*(24), Article 24. https://doi.org/10.3390/rs12244193

Tönissen, D. D., & Schlicher, L. (2021). Using 3D-printing in disaster response: The two-stage stochastic 3D-printing knapsack problem. *Computers & Operations Research*, *133*, 105356. https://doi.org/10.1016/j.cor.2021.105356