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Resilience in Construction Robotics and Human-Robot Teams for Industrialised Construction

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Abstract
Recent conversations in the built environment have been centered on the need for the built environment to be resilient and responsive. This has become imperative due to recent shock events such as the pandemics, which has revealed the sector's vulnerability in the face of shock events. However, sectors cannot be resilient and responsive when systems, processes and workflows are not built to be resilient. This paper, therefore, brings to the fore issues on the resilience of construction robotics, indicators for resilience in construction robotics, and why resilience is inevitable. Through a PRISMA construed systematic literature review, the paper links different theories and concepts from the social sciences and engineering to answer its applicability to the research objectives for built environment resilience. The study's findings inspire further conversations on the resilience of emerging digital technologies for the fourth industrial revolution and their potential to achieve a resilient and responsive AEC sector.

Keywords
Resilience, Construction Robotics, Human-Robot Teams, AEC

1. Introduction

Building new construction processes, workflows, and methods is integral to the emergence of fourth industrial technologies in the face of rapid urbanisation and shock events that require the AEC sector to adapt to increasing infrastructure delivery. Industrialised construction can improve construction processes by adopting automation and robotics (Rad, Mojtahedi and Ostwald, 2021). This has been necessitated by declining productivity, delivery of infrastructure on schedule, high incidence of hazards and risk on-site, the strain on construction workers, shortage of skills due to ageing workforce and the overall need to improve quality. As signified by Autodesk (2019), there would be a major increase in the use of industrialised construction (IC) to deliver infrastructure by 2035. By using IC, you can reduce labor costs, improve safety, decrease delays, improve product quality, enhance productivity, and improve dexterity - things that traditional construction methods would not normally accomplish (Bogue; 2018, Autodesk, 2019; Andersson, Cäker, Tengblad, and Wickelgren, 2019). With the need for manufacturers of autonomous systems, robotics, and collaborative robots to converge and mass-produce highly bespoke complex systems for construction usage, it is imperative to improve these systems' ability to aid the construction industry's resilience. Systems in an environment must be resilient to afford resilience to the environment. Moreso, autonomous systems must be resilient to deal with unanticipated circumstances in improving the overall responsiveness of the AEC to shock events (Zieba et al., 2009). Resilience describes how a human-machine system responds to unforeseen events, whether technical systems failures, human errors, or external circumstances (Zieba et al., 2009). Conversations on driving research and discussions on resilient robotics and collaborative teams are important to reinforcing the existing vulnerabilities in the built environment.

If not resilient and able to respond, collaborative construction robots could easily be relegated to tools or equipment rather than perceived as teammates on a worksite. Resilience is imperative to improve construction collaborative robots' productivity, durability, and reliability. Therefore, given the preceding, this study avails existing insights in resilience for autonomous systems, identifies indicators for resilience in construction robotics and highlights the importance of resilience in construction robotics to achieve a responsive AEC sector.

2. Methods

This work is based on a Systematic Literature Review(SLR) conducted to identify scientific papers discussing and evaluating resilience in autonomous systems, indicators for resilience and the importance of resilience in construction robotics adoption. According to Dieste et al. (2021) SLR method handles scientific research document analysis in a precise, transparent, and explicit manner. The methodical, explicit, and repeatable strategy used in this method, which involves several steps, ensure rigour and comprehensibility in the literature review process. The keywords of the study were searched in electronic search engines such as Google Scholar, Emerald Insight, Web of Science, Scopus, and ScienceDirect. These databases are extensive and can be accessed by academic institutions. Some databases offer advanced search capabilities that can help find relevant studies more precisely.

Furthermore, these databases have been used in similar studies related to construction robotics and resilience. Multiple databases expanded the search scope while minimising biases associated with a single database (Tennakoon et al., 2021). The defined keywords are linked using Boolean connectors "AND" to facilitate an advancedsearch related to the research area in these search strings. To avoid errors in selecting studies and avoid methodologicalerrors, efforts were made to assess and examine search terms and inclusion and exclusion criteria to minimise errors (Nwajei, 2021). The inclusion and exclusion criteria are shown below in Table 1

Table 1: Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion criteria
Must be written in English	Not written in English
Documents must be peer-reviewed journals and book chapters	Any publication, not peer-reviewed journal or book chapter
Must be built environment and/or construction industry	Not related built environment and/or construction industry

This systematic review is conducted using PRISMA, a widely recognised standard procedure for conducting systematic reviews and meta-analyses. This way, the review can be planned before starting, and methods can be justified for their applicability while avoiding biased decisions (Wijewickrama et al., 2020).

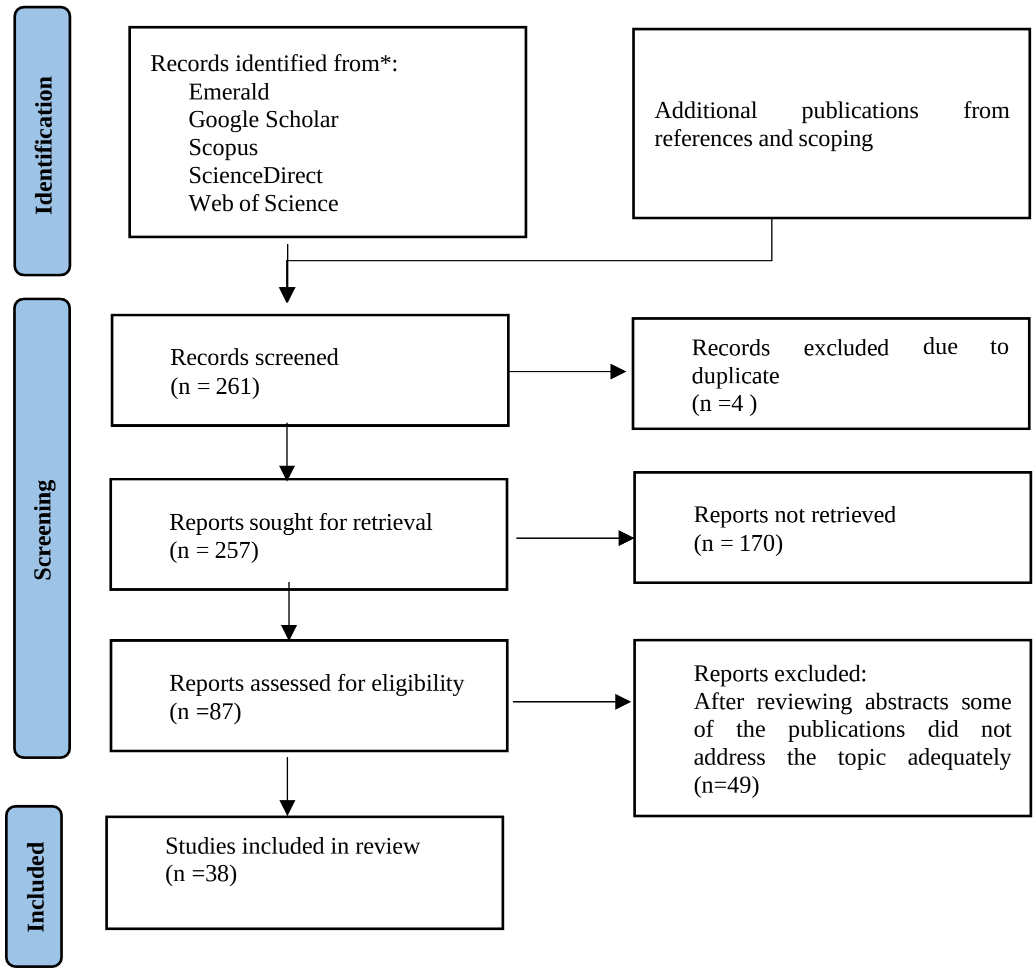

Fig 1. Research Method using PRISMA approach (Adapted from Page et al. (2021)

3. Results and Discussion

3.1 Wave of Publication Outputs

As demonstrated in Fig 2, construction robotics resilience studies are emerging in the AEC sector with low output in publications signifying constrained conversations on the thematic area. Given post-covid-19 research development and interests, it is projected that these areas will grow significantly as researchers are beginning to rethink the resilience of the construction sector.

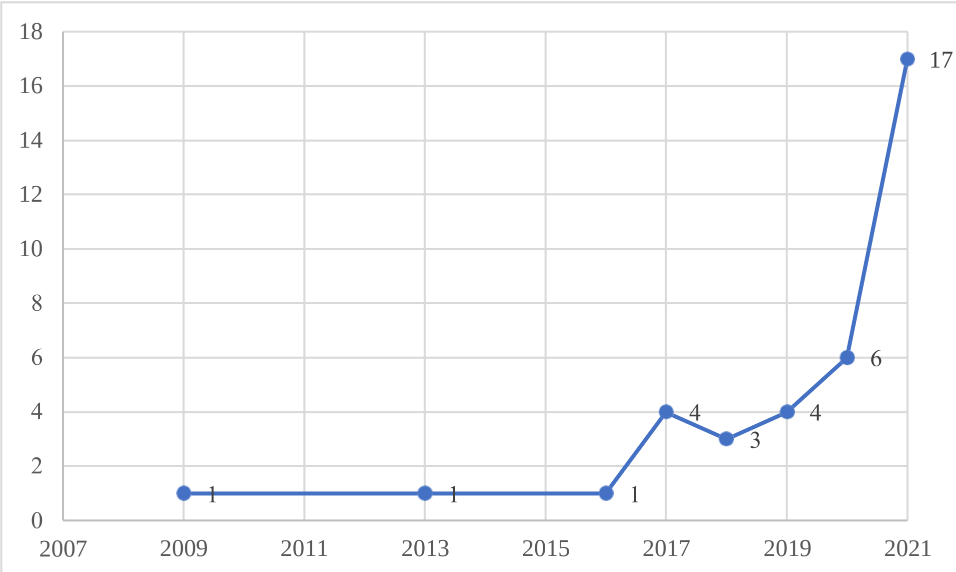

Fig 2. Research Method using PRISMA approach (Adapted from Page et al. (2021)

3.2 Overview of Important Documents towards resilience in construction robotics

Table 2 presents the research themes with directions towards the emerging conversation on the resilience of robotics in the construction industry. The thematic areas are discussed further in the next section.

Table 2: Research themes, study aims and method approach

Title	Authors/year	Aim	Method	Publisher
A Survey on Blockchain in Robotics: Issues, Opportunities, Challenges and Future Directions	Aditya, Singh, Singh, Kalla, 2021	A review of blockchain technology	literature review	Journal of Network and Computer Applications
Creating a case for innovation acceleration in the New Zealand building industry	Adafin, Rotimi, MacGregor, Tookey, Potangaroa, 2021	Pathways to Innovation acceleration	Mixed method	Construction Innovation
Systematic analysis of driverless technologies	Edwards,Akhter, Rillie, Chileshe, Lai, Roberts, Ejohwomu, 2021	Barriers, adoption issues, current development processes in driverless technologies	Mixed method and SLR	Journal of Engineering, Design and Technology
Toward digitalisation in the construction industry with immersive and drones technologies: a critical literature review	Elghaish, Matarneh, Talebi, Kagioglou, Hosseini, Abrishami, 2021	Literature review on digitatlization of the construction industry	SLR	Smart and Sustainable Built Environment
Digital project driven supply chains: a new paradigm	Bhattacharya and Chatterjee, 2021	Proposed an integrated framework for digital project-driven supply chains (PDSC) in AECO value chain.	Mixed method	Supply Chain Management: An International Journal
3D-Printing of Ultra-High-Performance Concrete for Robotic Bridge Construction	Javed, Mantawy, Azizinamini, 2021	Framework and performance metrics for materials and 3D-printing systems for bridge applications.		Journal of the Transport Research Board

Augmented reality and digital twin system for interaction with construction machinery	Hasan, Lee, Moon, Kwon, Jinwoo, Lee, 2021	AR & Digital Twins for Construction machinery	Model	Journal of Asian Architecture and Building Engineering
Industry 4.0, Disaster Risk Management, and Infrastructure Resilience: A Systematic Review and Bibliometric Analysis	Habibi, Mojtahedi, Ostwald, 2021	Analysed the application of I4.0 in disaster risk management	A Systematic Review and Bibliometric Analysis	Buildings
Propositions for a Resilient, post-COVID-19 Future for the AEC Industry	Nassereddine, Seo, Rybkowski, Schranz, Urban, 2021	Propositions for a resilient, post-COVID-19 future for the construction industry	literature review and modelling	Frontiers in the built environment
Robotic technologies for on-site building construction: A systematic review	Gharbia,Chang - Richards, Lu, Zhong, Li, 2021	A systematic review on robotics technologies for on-site building construction.	Systematic literature review	Journal of Building Engineering
Cloud Manufacturing, Internet of Things-Assisted Manufacturing and 3D Printing Technology: Reliable Tools for Sustainable Construction	Singh et al, 2021	The opportunities and challenges of construction digital technologies to achieve sustainability.	Literature review	Sustainability
Robotics as an Enabler of Resiliency to Disasters: Promises and Pitfalls	Wang et al, 2021	Examines how robots can make human and natural environments more resilient	Literature review	Resilience in the Digital Age
The Integration of Lean and Resilience Paradigms: A Systematic Review Identifying Current and Future Research Directions	Rad, Mojtahedi and Ostwald, 2021	SLR of articles context-intervention-mechanism outcome framework	Systematic Review	Sustainability
Modelling construction 4.0 as a vaccine for ensuring construction supply chain resilience amid COVID-19 pandemic	Osunsanmi, Aigbavboa, Thwala and Molusiwa, 2021	Modelled construction 4.0 as a tool for supply chain resilience in the construction industry.	survey questionnaire	Journal of Engineering, Design and Technology
A systematic review of factors affecting post-disaster reconstruction projects resilience	Charles, Chang-Richards and Yiu, 2021	literature on resilience factors applied to post-disaster reconstruction projects	SLR	International Journal of Disaster Resilience in the Built Environment
Trusting Automation: Designing for Responsivity and Resilience	Chiou and Lee, 2021	Reviewed articles related to human trust in automation in complex work environments	Literature review	Human Factors and Ergonomics Society
Towards commissioning, resilience and added value of Augmented Reality in robotics: Overcoming technical obstacles to industrial applicability	Jens Lambrecht, Kästner, Guhl , Krüger, 2021	Presents approaches towards distributed, hardware-agnostic microservice architecture with standard interfaces	Literature review	Robotics and Computer–Integrated Manufacturing
Ontology-based semantic modelling to support knowledge-based document classification on disaster-resilient construction practices	Dhakal, Zhang, Lv, 2020	Ontology-based semantic model for representing disaster resistance in construction job sites	Ontology development	International Journal of Construction Management
Distributed Situational Awareness in Robot Swarms	Jones, Milner, Sooriyabanda,Hauert, 2020	Provides situational awareness on swarms of low-cost robots	literature review	Advanced Intelligent Systems
Construction Automation and Robotics for High-Rise Buildings: Development Priorities and Key Challenges	Cai et al, 2020	Examined future development of robotics in the construction and maintenance of high-rise buildings	Quantitative research using Questionnaire surveys	Journal of Construction Engineering and Management
COVID, resilience, and the built environment	Keenan, 2020	Examined relationships between public and private sector resilience planning activities	Literature review	Environment Systems and Decisions

A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0	Ivanov & Dolgui, 2020	Presents a notion of a digital supply chain twin through a computerised model that represents network states for any given moment in real time		Production Planning & Control
Robotic technologies for on-site building construction: A systematic review	Gharbia, Chang-Richards, Lu, Zhong , Li, 2020	Provides a systematic review of robotics for on-site building construction	Literature review	Journal of Building Engineering
Towards on-site, modular robotic carbon-fibre winding for an integrated ceiling structure	Reinhardt et al, 2019	Research and development of robotic carbonfibre winding of an integrated ceiling structure for flexible workspaces scenarios	modelling	Construction Robotics
Constructing living buildings: a review of relevant technologies for a novel application of biohybrid robotics	Heinrich et al, 2019	Reviewed relevant technologies within construction automation and structural engineering	Literature review	Journal of Royal Society Interface
Building traits for organisational resilience through balancing organisational structures	Andersson, Cäker,Tengblad, Wickelgren, 2019	Describes and explains how balancing organisational structures can build traits for organisational resilience	Qualitative	Scandinavian Journal of Management
Deep Learning for Critical Infrastructure Resilience	Andersson, Cäker, Engblad and Wickelgren, 2019	Presents deep learning and critical infrastructure protection and illustrates how deep learning can improve resilience	Case Study	Journal of Infrastructure Systems
Digital skin of the construction site Smart sensor technologies towards the future smart construction site	Edirisinghe, 2018	Developed the concept of the digital skin of the future smart construction site.	Systematic and hierarchical literature review	Engineering, Construction and Architectural Management
What Are the Prospects for Robots in The Construction Industry?	Bogue, 2018	The present uses and potential future roles of robots in the construction industry	Literature review	Industrial Robot
Defining resilience for the US building industry	Kurth, Keenan, Sasani & Linkov, 2018	Presents opportunities and limitations for mainstreaming resilience into building industry processes and actors	Literature review	Building Research & Information
Briefing: UK-RAS white paper in robotics and autonomous systems for resilient infrastructure	Fuentes, Chapman, Cook, Scanlan, Li, Richardson, 2017	A briefing of the published UK-Robotics and autonomous systems (RAS) network	Literature review/ white paper	Smart Infrastructure and Construction
Contextualising mainstreaming of disaster resilience concepts in the construction process	Amaratunga, Malalgoda and Keraminiyage, 2017	Presents knowledge base of construction professionals on disaster resilient society	Interviews/Focus Group	International Journal of Disaster Resilience in the Built Environment
Resilient Robots: Concept, Review, and Future Directions	Zhang, Zhang and Gupta, 2017	Review on recent developments in the emerging field of resilient robots and the related robots that share common concerns with them	Literature review	Robotics
Self-Healing and Damage Resilience for Soft Robotics	Bilodeau and Kramer, 2017	Review on the state-of-the-art in damage resilience and self-healing materials and devices as applied to these three pillars.	Literature review	Frontiers in Robotics
Quantifying resilience	Angeler and Allen, 2016	looks at resilience terms, concepts and quantifies resilience	literature review	Journal of Applied Ecology

Survey and Introduction to the Focused Section on Mechatronics for Sustainable and Resilient Civil Infrastructure	Li et al, 2013	looks at research progress on the construction automation in the built environment	Systematic literature review	IEEE/ASME Transactions On Mechatronics

3.3 Theoretical background to resilience in construction robotics and human-robot teams

In industrialised construction (IC), more innovative and integrated techniques link the design of processes and systems (Autodesk, 2019). While the definition of resilience is understood on the surface level, conceptual and mathematical modeling is needed to broaden its applicability (Hoorn, 2018). The OECD outlines resilience as "the capacity for a system to absorb disturbances, recover from disruptions, and adapt to changing circumstances while retaining essentially the same function as before they were disrupted" (OECD, 2019; Chiou & Lee, 2021). Different concepts in resilience have identified it as resilience: rebound, which restores the system to its normal state after disruption, and robustness, which reacts to disruptions effectively. By introducing adaptations and emergence of new solutions within the system of functioning, resilience lies beyond the notion of robustness (Zieba et al., 2009; Li et al., 2013). The ability of construction robotics to be resilient is embedded in that errors of all kinds can be anticipated, reacted to, recovered from, and even learned from (Zieba et al., 2009; Edirisinghe, 2018).

In creating a case for innovation, Adafin et al. (2022) investigated how technological innovations can be enhanced within the New Zealand built sector to improve resilience in productivity. Through collating experiences, the study found that case studies are imperative in advancing the merits of showcasing the benefits of robotics. Further found that government interest is imperative to adoption. As adoption is imperative for improvement in design necessary to achieve resilience, the government must make strategic contributions through incentives and focus on knowledge development. While Edirisinghe (2019) supports this assertion, it also reiterated that heterogeneity of construction workplaces, social complexity of stakeholders, dynamicity of construction activities are factors needed to consider in designing resilient construction robotics. The study further discussed the importance of hardware, communication technologies, and software to support needed digital infrastructure in a collaborative environment. Driverless technologies enhance resilience in robotics as they offer the advantages of remote-controlled workflows vital for high risk and hazardous construction sites. Edwards et al. (2021) affirm this by also stating fusion of technological technical know-how with industry-specific knowledge is important to drive these advancements. Elghaish et al. (2021) assessed the status of adopting UAVs and indicated that while they are innovations, their versatility in applications to achieve resilience is widening. However, licensing and approval to fly are challenges facing the adoption and improvement of these technologies.

3.4 Indicators of Resilience in Construction robotics design for industrialised networks

Resilience is less discussed in construction robotics (Nassereddine et al., 2021). It is, however, imperative to achieving sustainable infrastructure delivery. Resilience in the context of robotics for construction has been defined with indicators as identified by Fiksel (2003), Zieba et al. (2009), and Hollnagel and Woods (2006). They are.

Cooperativeness: Construction robotics for deployment on industrialised construction sites would not operate in silos but in collaborative tasks. In human-robot teaming, cooperativeness is essential in building trust, understanding tasks, and enhancing communication between robotics and humans (Chiou and Lee, 2021). This, therefore, involves the coordination of tasks, ordering of workflows, and choosing an effective team lead. However, the responsiveness of human workers to collaborate in these teams is underpinned by knowledge of the autonomous system, underlying beliefs/perceptions of robotics, assumptions, and socio-cultural implications (Chiou & Lee, 2021). However, resilience for autonomous systems in the built sector is considered how agents within a network cooperate and utilise shared resources when faced with unexpected challenges (Woods, 2015). Research by Friedland (1990) highlights that trust is most likely to flourish when both parties demonstrate genuine responsiveness to each other's needs, not only because trust is reciprocal (trusting because one feels trusted), but also because of the complex interaction amongthose involved. Enhancing the interaction between a human operator and a robot to optimise the use of their respective competencies is essential for improved cooperativeness

Adjustable Autonomy: Zieba et al. (2009) described this as the ability of robotics to adjust at any time for unplanned events to react to and optimise the distribution of tasks among humans and robots. Nassereddine et al. (2021) highlight that resilience is less about reducing the risk that returns a system to its previous position but more about adaptive capacity, which aids a system in adapting to a world permanently under transformation. For construction robotics to be resilient, they must integrate adjustable autonomy in designs.

Buffering capacity: Hollnagel and Woods (2006) defined this as the quantitative capacity of systems to cope with perturbation without adapting Zieba et al. (2009). Maintenance fears, breakdowns, loss or mechanical intolerance identified as fears associated with the adoption of construction robotics must be designed to withstand stress, strain, and external pressures to offer more effectiveness and justify the cost of procurement.

Margin and tolerance: This describes the behaviour of a system concerning a boundary of operations (Hollnagel and Woods, 2006; Zieba et al., 2009). Tolerance towards tasks and between teams is important. Nassereddine et al. (2021) stated that resilient teams tend to have members who can resolve conflicts. This is also important to avoid destructive tendencies from humans towards robotic teammates.

Flexibility: this describes the capacity of autonomous systems to adapt to new constraints (Hollnagel and Woods, 2006; Zieba et al. 2009). The construction sector is reputable for encountering engineering challenges necessitating flexibility in approach. This further reiterates the importance of integrating human, technical skills with the operational capacity of the robots.

Cross-scale interactions: Due to the importance of communication in collaborative systems, cross-scale interactions examine the communication between the different entities of the system. In examining the challenges to the resilience of robotics, Srinivas Aditya et al. (2021) mentioned this interaction embodies perception, cognition and action. It further explores a robot's sight, speech, thoughts, social awareness, proximity, autonomy and how humans perceive these robots. Understandable interaction in communication between collaborative teams in humans and robots must be driven towards enabling a trustworthy environment (Emaminejad et al., 2021). Courtemanche (2020) demonstrated the importance of this and stated relationships serve as the heartbeat of infrastructure projects and therefore is underpinned by the resilience of project teams members who play a key role in improving the overall resilience of the AEC sector.

Diversity: As Fiksel (2003) identified, diversity illustrates the availability of multiple forms and behaviours in the system (Zieba et al., 2009).

Efficiency is explained as focused on ensuring the system's performance while utilising modest resources (Fiksel,2003; Zieba et al., 2009).

Adaptability: This flexibility allows the system to react to different pressures. Situational awareness is vital to this; Jones et al. (2020) state that perception of the environment by the robot, comprehension of the situation in relation with the construction tasks to be executed, and situational awareness allows the construction robot to capture the state of the environment and act accordingly are essential in achieving resilience.

Cohesion: Describes a set of unifying patterns or links and interactions between the entities of an organisation to manage perturbations. To achieve this, future designs must factor in resilient physical practices, economic-resilient practices, social-resilient practices and environmental-resilient practices (Dhakal et al., 2020).

3.5 Importance of Resilience in Construction Robotics and human-robot teams' design

As stated by Bhattacharya and Chatterjee (2021), with the development of several technologies, the potentials of these systems are lost and not appropriately communicated to stakeholders (Bhattacharya and Chatterjee, 2021)

With deployment in hazardous areas, the incidence of damage is high, and self-regenerating properties are important for it to continue to function despite damages. An example of this is the black star robot (Habibi Rad et al., 2021). The investment cost of adopting robotics would be easily justifiable when robots are resilient and can adequately justify the cost-benefit. This is imperative as stakeholders are looking for investing in systems that last and endure. Maintenance and sustaining costs would be more reduced when resilience is designed into robots as they can repair themselves, sense, identify and remedy damages.

Furthermore, with the need of the built environment to be resilient and responsive in the face of shock events such as pandemics. Consequently, stakeholders' requirement is shifting from adopting and deploying robotics just for productivity and further to integrating resilience into infrastructure delivery (Cheshmehzangi 2021). Achieving sustainable infrastructure delivery depends on the industry's resilience, which cannot be achieved without resilient systems underpinning its execution and transformation (Courtemanche, 2020). Due to the unstructured nature of built environment construction projects and the unpredictability of hazards and topographical challenges in heavy engineering and mining works, robotics systems must be resilient to truly adapt to such environments and function optimally with zero human intervention. This is especially important in disaster management and construction during shock events to help address labour shortages, reduce safety issues, and deliver infrastructure needs (Habibi Rad et al., 2021). Resilience is imperative to how human collaborators perceive collaborative construction robots. Therefore, to build resilience in the AEC, Nassereddine et al.(2021) proposed; decentralisation of the operations of design and construction firms, early involvement of key project participants, industrialised construction, circular business models, remote working, integrated design management using BIM, resilience in staffing and skills training, reversible building design, AR-enabled applications, the shift to automation and 3D printing and Lean Construction.

4. Conclusion

Recent shock events have revealed the vulnerabilities in the AEC sector exacerbated by the continuous use of traditional construction systems, workflows, and processes with no enhanced productivity benefits. With emerging digital technologies, industry practitioners will be looking to maximise returns on infrastructure investment by adopting resilient robotic systems. In the aftermath of COVID-19, many studies are rethinking approaches to infrastructure to build resilient and sustainable infrastructure (Lauren, 2021). Shock events have demonstrated the importance of resilience in infrastructure in maintaining a continuous supply chain, logistics, and delivery of essential goods and services. This has underlined the need for countries to make their infrastructure more resistant to future disasters and pandemics. Governments can limit their exposure to fiscal risks over the lifetime of infrastructure assets by incorporating sustainability and resilience considerations into their infrastructure planning. Therefore, further studies must be conducted to sustain resilience in the face of shocks, considering how interconnected systems incorporating technologies, systems, and humans within the industry can utilise shared strengths to adapt to shocks. This means anticipating, reacting, recovering, and learning from different kinds of errors. Therefore, this study avails a review of conversations on resilience in construction robotics, its importance, and indicators for the design and development of resilient robotics in industrialised construction.

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References

Adafin, J., Wilkinson, S., Rotimi, J. O. B., MacGregor, C., Tookey, J., & Potangaroa, R. (2022). Creating a case for innovation acceleration in the New Zealand building industry. *Construction Innovation*, *22*(1), 185–204. https://doi.org/10.1108/CI-10-2018-0081

Autodesk. (2019). *Industrialised construction in academia*. 1–30. https://damassets.autodesk.net/content/dam/autodesk/www/pdfs/autodesk-industrialized-construction-report.pdf

Bhattacharya, S., & Chatterjee, A. (2021). Digital project-driven supply chains: a new paradigm. *Supply Chain Management*, *2*(April 2021), 283–294. https://doi.org/10.1108/SCM-12-2020-0641

Chiou, E. K., & Lee, J. D. (2021). Trusting Automation: Designing for Responsivity and Resilience. *Human Factors*. https://doi.org/10.1177/00187208211009995

Dhakal, S., Zhang, L., & Lv, X. (2020). Ontology-based semantic modelling to support knowledge-based document classification on disaster-resilient construction practices. *International Journal of Construction Management*, *0*(0), 1–20. https://doi.org/10.1080/15623599.2020.1765097

Edirisinghe, R. (2019). Digital skin of the construction site: Smart sensor technologies towards the future smart construction site. *Engineering, Construction and Architectural Management*, *26*(2), 184–223. https://doi.org/10.1108/ECAM-04-2017-0066

Edwards, D. J., Akhtar, J., Rillie, I., Chileshe, N., Lai, J. H. K., & Roberts, C. J. (2021). *Systematic analysis of driverless technologies technologies*. https://doi.org/10.1108/JEDT-02-2021-0101

Elghaish, F., Matarneh, S., Talebi, S., Kagioglou, M., Hosseini, M. R., & Abrishami, S. (2021). Toward digitalisation in the construction industry with immersive and drones technologies: a critical literature review. *Smart and Sustainable Built Environment*, *10*(3), 345–363. https://doi.org/10.1108/SASBE-06-2020-0077

Emaminejad, N., Akhavian, R., & Ph, D. (2021). Trustworthy AI and Robotics and the Implications for the AEC Industry: A Systematic Literature Review and Future Potentials. *ArXiv*, *2*, 1–29. https://arxiv.org/ftp/arxiv/papers/2109/2109.13373.pdf%0Ahttps://arxiv.org/abs/2109.13373

Habibi Rad, M., Mojtahedi, M., & Ostwald, M. J. (2021). Industry 4.0, disaster risk management and infrastructure resilience: a systematic review and bibliometric analysis. *Buildings*, *11*(9). https://doi.org/10.3390/buildings11090411

Hoorn, J. F. (2018). From Lonely to Resilient through Humanoid Robots: Building a New Framework of Resilience. *Journal of Robotics*, *2018*. https://doi.org/10.1155/2018/8232487

Jones, S., Milner, E., Sooriyabandara, M., & Hauert, S. (2020). Distributed Situational Awareness in Robot Swarms. Advanced Intelligent Systems, 2(11), 2000110. https://doi.org/10.1002/aisy.202000110 Lauren, T. (2021). Building Resilience.

Nassereddine, H., Seo, K. W., Rybkowski, Z. K., Schranz, C., & Urban, H. (2021). Propositions for a Resilient, Post-COVID-19 Future for the AEC Industry. *Frontiers in Built Environment*, *7*(July), 1–16. https://doi.org/10.3389/fbuil.2021.687021

Srinivas Aditya, U. S. P., Singh, R., Singh, P. K., & Kalla, A. (2021). A Survey on Blockchain in Robotics: Issues, Opportunities, Challenges and Future Directions. *Journal of Network and Computer Applications*, *196*(March 2021), 103245. https://doi.org/10.1016/j.jnca.2021.103245

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety*, *141*, 5–9. https://doi.org/https:// doi. org/ 10. 1016/ j. ress. 2015. 03.018

Zieba, S., Polet, P., Vanderhaegen, F., & Debernard, S. (2009). Resilience of a human-robot system using adjustable autonomy and human-robot collaborative control. *International Journal of Adaptive and Innovative Systems*, *1*(1), 13. https://doi.org/10.1504/ijais.2009.022000