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Integrating Industry 4.0 Technologies into the Disaster Management Lifecycle: A Comprehensive Review

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***Abstract*:**

In recent times, Industry 4.0 (IR 4.0) has ushered in a digital revolution across various industrial processes, fundamentally reshaping the landscape of cyber-physical systems. These advancements necessitate their integration into the realm of disaster management. This article's primary objective is to explore the current trends in IR 4.0 technologies and their profound influence on the procedures involved in disaster management. The article delves into the core concepts of IR 4.0, alongside industry practices that accompany them, while also examining the potential for their adaptation within the disaster management lifecycle, drawing insights from the latest literature. The phases of disaster management are thoroughly examined within this article, highlighting the pivotal role played by contemporary technology at each stage. The article meticulously scrutinizes the opportunities presented by information and communication technology, the internet of things, wireless sensor networks, big data analytics, artificial intelligence, and robotics at various junctures of the disaster management cycle. Ultimately, the article proposes a comprehensive platform as a sustainable solution, offering recommendations that can be invaluable to disaster management planners and practitioners.

***Keywords*: IR 4.0, Disaster Management Cycle, Information and Communication Technology, Internet of Things, Wireless Sensor Networks, Big Data, Artificial Intelligence, Robotics**

1. Introduction

Tsunamis, storms, earthquakes, volcano eruptions, floods, and pandemic crises like COVID-19 have affected the humanity on Earth in recent years. The majority of disasters and related emergencies strike without warning, disrupting human routines, claiming lives and causing property damage. From 2002 to 2012, the United Nations Office for Disaster Risk Reduction (UNISDR) recorded 1.29 million deaths, 2.9 billion people impacted, and $1.7 trillion in losses, with a consistent increase in annual disasters (Reich, 2016). According to 'One World in Data,' there has been a rise in the number of such events in recent years (Ritchie & Roser, 2014), as shown in Fig. 1.

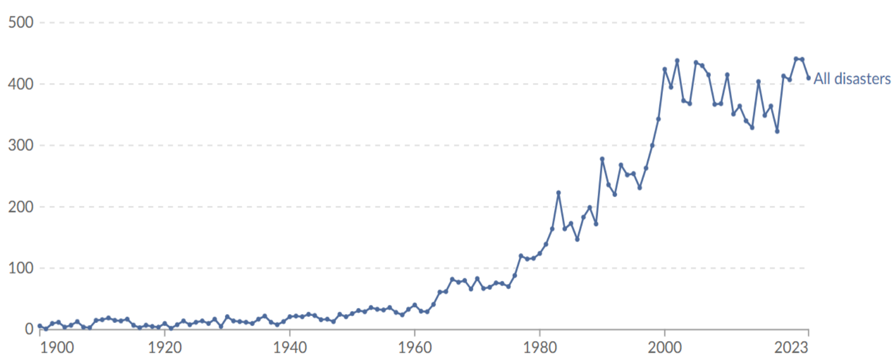

Figure 1: Record of Natural Disasters (Ritchie & Roser, 2014)

Following the nuclear tragedy in Fukushima, Pascal claims that high-tech countries are creating their own risks through Nat-Tech threats (Peduzzi, 2019). This has resulted in a new perception of risk, as well as the assumption that natural disasters can no longer be classified as such. The tally is influenced by both man-made and natural disasters. In the case of natural disasters like East-Japan earthquake, severe weather in Americas and fires in Canada, the conventional means of communication were compromised or completely destroyed. The rescue operations were affected by the communication system damages, putting the rescue workers and victims in danger as the rescue workers needed to communicate and deliver multimedia communication to the control station (Hayajneh, Zaidi, McLernon, & Ghogho, 2016). Key event management is critical for reducing crisis impacts and saving lives, and it has been a source of discussion for the community, particularly crisis managers. Emergency decision-making is generally a difficult and demanding task due to the complexity, unpredictable nature, and time constraints involved with emergency situations (Fogli & Guida, 2013). One of the most crucial aspects of emergency management is catastrophe recovery. It is the responsibility of disaster managers to protect communities by employing appropriate solutions. Typically, disaster management frameworks are based on risk assessment and management, and major challenges arise as a result of emergency response incapability, decision-making delays, and policy and procedural issues.

IR 4.0 is a set of cyber-physical technologies that can be used in a variety of practical domains, including disaster management. The developments in IR 4.0 can aid disaster managers in getting early warnings, making preparations, informing stakeholders, making timely and better decisions, assisting in the recovery process, and estimating damages (Wollschlaeger, Sauter, & Jasperneite, 2017). Even natural risks are not always natural, according to climate and environmental specialists. Climate and environmental changes induced by humans have an impact on risk probabilities. Natural and man-made disasters have a detrimental influence on the economy and society, resulting in a high number of deaths, injuries, and infrastructure damage (Bannour & Ben Ghezala, 2021). Natural disasters also have an impact on socioeconomic norms, indicating that a better understanding of long-term disaster estimations, management, and recovery procedures is required as part of the national and international framework. Dealing with disasters necessitates careful preparation, and the concept of disaster management sustainability is a growing trend in research. Because disasters allow us to change our social norms, civilizations throughout the world must continue to explore and learn about the critical activities that must be made to reduce the impact of disasters. The research presented in (Rad, Mojtahedi, & Ostwald, 2021) examines disaster management in light of industry's digital developments. 4.0. However, achieving long-term management is a topic that has received little attention. It is also necessary for social scientists to collaborate with technologists in order to use technology in research while maintaining a balance between social and physical sciences. This study aims to understand disaster management in the context of shifting demands posed by rapid industrial growth.

2. Main Components of Disaster Management Cycle

Natural disasters are uncontrollable, but their impact can be reduced by employing various disaster management approaches. Emergency management is viewed as a four-phase procedure by the majority of academics (Joyce, Wright, Samsonov, & Ambrosia, 2009). Authors in (Zhang, Wang, & Wang, 2018) identified a number of studies that describe emergency management as a complex and difficult task including a variety of management strategies implemented by emergency managers and stakeholders. It aims to prevent unanticipated events, limit societal and economic losses, and lessen the effects of catastrophic calamities. The disaster management cycle as illustrated in Fig.2. is a continuous process working in four evident phases.

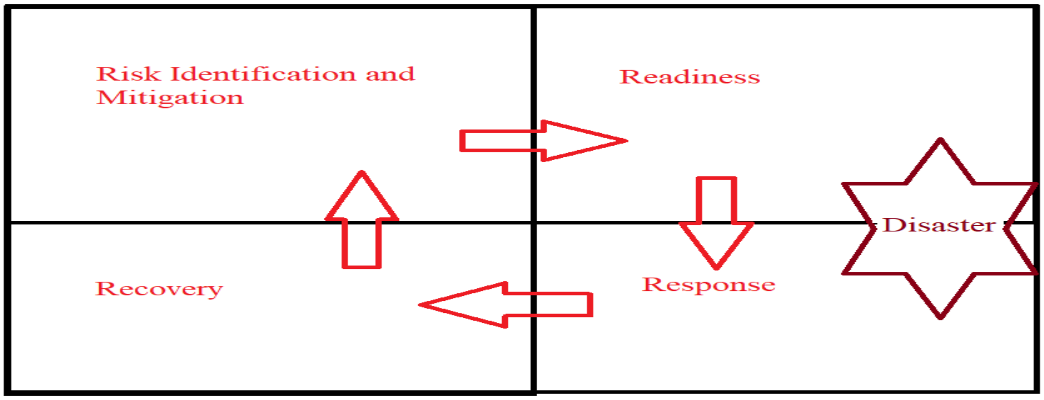

Figure 2: Phases of Disaster Management Cycle

The period of risk identification and mitigation begins long before an emergency occurs. It is a term that refers to measures and decisions taken in order to minimize the population's sensitivity to future unavoidable disasters (Liu, Zhou, Hu, & Zhao, 2009). People and property can be protected by mapping, surveillance, and observation. This phase focuses on long-term measures such as building regulations enforcement, infrastructure development (for example, rerouting roadways away from disaster-prone areas), and shelter allocation. The goals of the readiness phase are to strengthen the capabilities of emergency response teams (Zhang, Wang, & Wang, 2018). It comprises a variety of activities, such as creating and reviewing emergency plans, predicting the effects of a specific disaster, and training emergency responders. During this stage, activities to strengthen the civilian population's resilience are implemented, such as volunteer training and evacuation exercises, which fall under the readiness phase.

The reaction phase begins immediately following a catastrophic event and ends once the situation has been settled. Public safety communication, search and rescue, spreading emergency messages, first response, and monitoring activities are all possible recovery tasks. The goal of this phase is to save lives while also minimizing economic and environmental damage. The reaction phase is the most challenging and thus the most researched because these commitments are frequently completed under duress, anxiety, and ambiguity. Evacuation, search and rescue efforts, resource mobilization, and medical treatment are among the steps used during this phase (Zhang, Wang, & Wang, 2018).

Additionally, initiatives to increase the civilian population's resilience are implemented throughout this time period, such as volunteer training and evacuation drills that come under the preparedness phase. The recovery phase begins immediately after the emergency situation has been resolved, and it focuses on restoring normalcy to the affected people. It includes a wide range of duties, such as estimating, repairing, and rebuilding property damaged or destroyed by a specific disaster, restoring important services, and revitalizing the local economy, among others (Zhang, Wang, & Wang, 2018). In (Harrison & Johnson, 2016), the authors addressed crowdsourcing communication platforms during and after disasters and characterized crowdsourcing by US and Canadian government agencies at all stages of the disaster management cycle. Around the world, a variety of similar disaster management approaches are utilized, with the most crucial commodity being response time, because delays can have negative repercussions (Câmara, 2014).

3. Supporting Risk Management Cycle using Advance Technologies

The capacity to understand economic, social, and environmental changes must be prioritized in disaster risk reduction. Leading international organizations such as UNISDR and the World Bank's insurance models have failed to adequately address environmental hazards. These organizations are still fixated on catastrophic events and have failed to recognize emerging threats. Furthermore, when risk complexity grows, side effects emerge, necessitating the examination of the risk framework by specialists from many domains. Technologists, IT experts, civil engineers, land planners, social scientists, economists, development specialists, and climate and environmental scientists are now part of the risk community. This list will only grow, but not everyone is open to cross-disciplinary collaboration or can think outside the box.

Advanced technologies have demonstrated their use in effectively managing emergencies, which should be reflected in regulations. Assessors and controllers are aided by IR 4.0 tools in determining the degree of hazards. Early soil erosion, for example, and its consequences on floods, landslides, and stream siltation are now more affordable and controlled to estimate. The United Nations has called for a paradigm shift away from catastrophe management and toward risk management or managing for long-term development (Brundiers & Eakin, 2016). The success of emergency forecasting, response, and recovery should be systematically examined and fed back to the policy elements of decision-making. In this regard, the following subsections outline possible technology fields.

3.1 Connectivity, Information and Communication Technologies (ICT) Usage and Ad-hoc Deployment in Disaster Management

The latest communication technology can be used to handle various stages of disaster management. The pre-disaster mitigation and post-disaster recovery processes in climate-related disasters necessitate the rapid deployment of improved alternate means of communication systems to early warn and monitor the target areas. These tasks could be aided by sending multimedia data, such as environmental monitoring data and surveillance recordings, to the ground control station so that the disaster manager can take appropriate action. Emergency messages and ad-hoc wireless communication are also required for active mobile users or end users in disaster-affected areas. Following a tragedy, public safety communication becomes vitally important, requiring first responders to communicate and coordinate efficiently. The Spectrum Act 2015 was passed by the United States Federal Commission of Communication and Congress in response to the importance of communication and its necessities. Using the 700 MHz frequency range, this act aims to create a separate communication network for public safety operators and aims to assist public safety operators in establishing a nationwide public safety broadband communication network that will allow authorities to coordinate and communicate voice, video, photos, and data.

Other advances in information communication technology, such as social media and remote sensing, have made a significant contribution to all four phases of the management cycle. Risk identification and risk registration can both benefit from the use of ICT. ICTs can be used to improve awareness, mitigation efforts, and early warning systems. ICT is a useful tool for quick response and can aid in recovery activities. Roadside aiding relays, UAVs, drones, or balloons as aerial relays, and satellites establishing communication linkages might all be used to construct this ad-hoc communication. This ad-hoc communication can be based on Table 8 of the ITU-R M.2171-2009 report, which specifies a total bandwidth requirement of 34 MHz for uplink and 18.1 MHz for downlink to establish ad-hoc communication (Bashir & Yusof, 2022).

Near-real-time data distribution using modern ICT techniques can also help with pre-disaster and post-disaster management efforts. Delay-tolerant networks, the Internet of Things (IoT), mobile networks, satellite networks, and current applications that use global positioning system (GPS) can all help manage disasters and save lives and property. ICTs can also help with the evacuation process and post-disaster estimation, but a comprehensive ICT model is needed to allow disaster management organizations to take advantage of emerging technology and increase their efficiency. Policies and regulations must be devised, shared, and harmonized among countries in order to achieve standardization.

3.2 Big Data, IoT and Wireless Sensor Networks (WSNs)

ICT contributes to the massive amount of data generated every second around the world. A great amount of data is currently being generated from numerous sources, which can be used to assist disaster management in analysing and taking appropriate quick steps. The ability to collect, analyse, and evaluate data is improving all the time. The information provided by network nodes in IoT and WSNs should be analysed for decision-making. One of the technology research areas is ensuring that information reaches the intended destination in the shortest possible time (Lwin, Sekimoto, Takeuchi, & Zettsu, 2019). Disaster managers can use IoT, sensors, and gadgets to collect data from a wide region in order to control a collection of robots deployed to do disaster-related duties. Effective algorithms for node deployment, data collecting, and processing can yield effective results. In post-disaster recovery missions, using WSN and satellite-supported methodologies to conduct a spatial analysis of the environment and deployment locations has proven to be effective (Zhang, Wang, & Wang, 2018).

3.3 Robotics, Artificial Intelligence (AI) and Automation

In disaster management, collaboration across numerous machines or vehicles is critical. With a focus on collision avoidance, an efficient cooperative network of many robots was described combining ant colony and Q-learning algorithms for pre and post-emergency management. The use of efficient algorithms to coordinate a swarm of robots doing coordinated activities is a popular issue among researchers (Abraham, et al., 2019). This work sought to assist rescue workers by employing UAVs and an algorithm to find persons buried beneath debris, provide first aid, and provide visuals of the hazardous site to disaster managers. Authors (Mandow, Serón, Pastor, & García-Cerezo, 2020) discussed the use of robots by rescue teams to remove humans from hazardous and disaster-affected places in two parts. The efficient steering and teleoperations of the robots were the main emphasis of this research. In (Murphy, 2016), the authors provided three case studies that used ICT, UAVs, and social media to identify main operational constraints. The study reported in (Yinka-Banjo, Osunmakinde, & Bagula, 2017) created a disaster management model for underground tunnels in the event of a calamity. Authors in (Tadokoro, 2015) discussed the issues posed by robotics in the East Japan Earthquake scenario. In addition to the technology in capabilities that are affecting catastrophe management, the author claims that societal adaptation to science and developing technologies is slower.

AI approaches can help with disaster management efficiency by assisting with planning, responding, assigning resources, repairing damages, and recovering activities. A number of studies have found that using AI approaches to handle data related to natural catastrophes can help disaster managers make quick and accurate decisions (Bashir & Yusof, 2019). Modern AI technologies can help with all four phases of disaster management, including mitigation, readiness, response, and recovery (Khan, 2008). Using simulations, AI technology has been utilized to assist crisis managers in making vital and successful decisions. Several AI-based methodologies, concepts, and systems have been presented in the literature to assist emergency management departments in responding to emergencies and enhancing the quality of their decisions. Image processing, for example, can be used to identify the damages and locations of those who have been affected by an earthquake. Deep learning, machine learning, supervised models, unsupervised models, reinforcement learning, and optimization are all AI strategies that can help with decision-making. To adequately simulate the environmental effects, many computational models are used.

Automation makes processes more efficient by transferring operations to machines with the least amount of human contact. Automation, as a distributed control method deployed on vehicles such as UAVs, can be extremely useful in disaster response. As in Industry 3.0, autonomous processes require a constant flow of data between controls, sensors, and actuators. The communication networks of IR 4.0 provide ideal platforms for strengthening automated processes to facilitate this data exchange (Sauter, Soucek, Kastner, & Dietrich, 2011). IR 4.0 trends such as IoT, device-to-device (D2D) networks, and cyber-physical space are reshaping automation processes in a variety of fields, including disaster management (Weinman, 2016). They provide higher levels of interconnectivity, cognitive decision making capability, data collection and dissemination, and cloud-based applications.

3.4 Unmanned Aerial Vehicles

The reachability of the disaster-affected area during immediate need of support is one major challenge faced by communities. This phase can be supported by using quadrotor UAVs or drones (ITU, 2009) (Bashir, Iqbal, & Yusof, 2022). If UAVs are used in such situations, UAVs can help to extend the communication range to those areas where there is no network coverage. UAVs are also a viable and cost-effective solution in providing ad-hoc communication services in next-generation networks compared to the ground static and costly fixed relays (Bashir & Yusof, 2019). UAVs associated with a terrestrial wireless network can be quickly deployed in areas that require urgent demand without any pre-installed infrastructures. UAVs in relay topology may serve some of the basic functions of a typical base station of a cellular communication network. Heterogeneous cellular networks having ground transceivers and aerial transceivers (like UAVs) working as relays (Li & Han, 2016) can improve the quality of communication links, can help in disaster recovery, can meet the coverage issues and can support wide IoT data collections. Due to these unique features, UAVs are now being utilized in a wide range of applications and it is expected that their number will skyrocket in two decades. The applications like collecting data, Location-Aware Services, Military Services, Safety, and Security Missions can be satisfactorily provided using FANETs.

As per the R M.2171 report of ITU (Union, 2009), the utilization of UAVs in UAV based Systems (UAS) can be classified into two main groups, commercial and governmental as shown in Fig. 3.

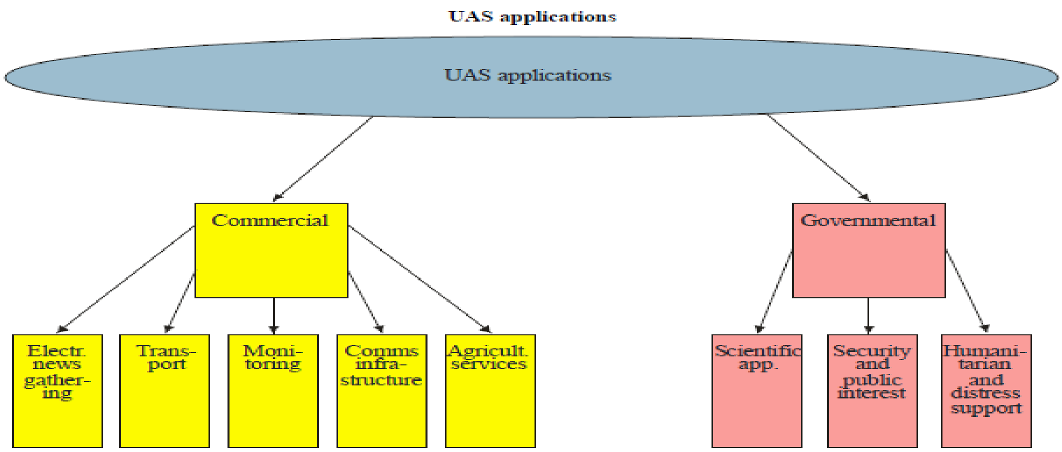

Figure 3: UAVs Utilization (Union, 2009)

This communication is based on the report by ITU-R M.2171-2009, Table 8 (Union, 2009), which asks for 15.9 MHz for uplink and 18.1 MHz for downlink totalling 34 MHz. Public safety communication followed by a disaster becomes extremely vital during emergency situations demanding first responders to communicate and efficiently coordinate. For example, immediately after an earthquake, the damages and locations of the afflicted people can be identified using image processing. United States Federal Commission of Communication and Congress has passed the spectrum act. This legislation is to build a standalone communication network for public safety operators (Security, 2020) using the 700 MHz frequency band. This act is to help public safety operators to create a national-level public safety broadband communication network so that authorities may coordinate and transmit voice, video, pictures, and data on it. In such climate-related disasters, the post-disaster recovery processes demand fast deployment of advanced alternate means of communication systems to monitor the affected area and rescue the victims.

4. Sustainability in Disaster Management

While disasters create possibilities for change, it is unclear who will be able to recognize and capitalize on these opportunities to speed up the transition to sustainability. Because they are based on human dispositions, perceptions of chances for change toward sustainability that benefit the larger good are distorted. For example, attitudes, social and economic capital, and sustainability experiences and contexts - such as governance structures, societal fault lines, and effect scope (Brundiers, 2018). Because existing disaster recovery procedures do not systematically promote sustainability, this article aims to describe the key concepts of disaster management that include sustainability. Local, national, and international planners can use the recovery management model's sustainability to help them put in place the necessary actions to strengthen the process.

A variety of components of sustainable recovery have been examined, but their integration into the implementation model has not been done at a mature level, according to the literature. The majority of planning done around the world focuses on natural hazards, according to the literature, but more regulation is needed for other sorts of manufactured hazards. As a result, further guidelines are needed to aid planners and practitioners. The catastrophe management framework must be developed around four inquiry concepts to achieve this:

1. Periodic thorough recovery planning evaluations are conducted at the local, national, and international levels, analysing the activities' successes and drawbacks. This should also include evaluations of various laws and their implementation over time around the world.

2. Redefining many parts of recovery management, with a focus on sustainability, based on periodic assessments, and redefining multiple policy levels.

3. To evaluate the adoption of several additional alternative disaster recovery plans, including options that might be applied or integrated into particular scenarios. These alternatives must be explored and reflected as part of the strategy, based on research findings that should be included in current frameworks.

4. Instilling in civilizations a culture of long-term disaster management. Investments in education, training and regulation may result in ethics that help society run more smoothly before, during, and after disasters.

5. Intelligent Disaster Response and Recovery Platform (IDRRP)

Since disasters can strike unexpectedly, causing immense human and economic losses, the development of an IDRRP is proposed there that leverages IR 4.0 technologies to transform disaster management procedures. The IDRRP as a comprehensive system can enhance all phases of the disaster management cycle of Fig. 2.

5.1 Risk Identification and Mitigation

- IoT Sensors and Data Analytics: Deploy IoT sensors in disaster-prone areas to collect real-time data on environmental conditions. Use AI-driven analytics to predict potential hazards and assess risk probabilities more accurately.
- Digital Twin Technology: Create digital twins of disaster-prone regions to simulate and evaluate the effectiveness of mitigation measures such as infrastructure development and land use planning.

5.2 Readiness

- Artificial Intelligence for Resource Allocation: Implement AI algorithms to optimize the allocation of emergency response resources, including personnel and equipment, based on real-time data and demand predictions.
- Virtual Reality (VR) Training Simulations: Develop VR training simulations for emergency responders to enhance their preparedness and decision-making skills.
- Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity that you use in an equation

5.3 Response

- Robotic Assistance: Utilize robotics, including drones and ground robots, for search and rescue operations. AI algorithms can help these robots navigate complex terrains and locate survivors.
- Augmented Reality (AR) for Field Operations: Equip responders with AR devices to access real-time information, maps, and instructions, improving their situational awareness.
- 5G Connectivity: Ensure high-speed 5G connectivity to support uninterrupted communication among response teams and enable the transmission of multimedia data

5.4 Recovery

- Big Data Analytics: Employ big data analytics to assess the extent of damage, prioritize recovery efforts, and optimize resource allocation for reconstruction.
- Blockchain for Supply Chain Resilience: Implement blockchain technology to track the flow of relief supplies and ensure transparency and efficiency in the distribution process.
- Renewable Energy Integration: Integrate renewable energy sources into critical infrastructure to ensure energy resilience during recovery phases.

5.5 Sustainability

- Continuous Evaluation: Regularly assess the performance of the IDRRP system, update algorithms, and incorporate lessons learned from previous disasters.
- Policy Adaptation: Develop agile policies and regulations that can adapt to evolving disaster scenarios and technological advancements.
- Alternative Recovery Plans: Explore various recovery scenarios and alternative strategies to diversify disaster response and recovery options.
- Disaster Management Education: Invest in education and training to instill a culture of long-term disaster management, emphasizing the responsible use of IR 4.0 technologies.

The IDRRP represents a cutting-edge solution for revolutionizing disaster management procedures. By harnessing the power of IR 4.0 technologies, IDRRP aims to enhance preparedness, response, and recovery efforts, ultimately reducing the impact of disasters on communities and promoting long-term sustainability in disaster management. Implementing the IDRRP requires collaboration among governments, technology providers, disaster management agencies, and researchers to ensure its effectiveness and adaptability to diverse disaster scenarios. Furthermore, ongoing research and development efforts should focus on refining the platform's capabilities and expanding its applicability to different regions and types of disasters.

6. Conclusion

After evaluating a variety of current state-of-the-art, it is clear that new technologies have the capacity to reshape processes, but there is a need for a new concept of crisis management in all phases, including the search for new cyber-physical spaces. Traditional methodologies and procedures must change, necessitating greater research at the academic and government levels to capture IR 4.0 requirements. The success and effects of implementing IR 4.0 digital transformation in disaster management should be investigated further. For a sustainable future, the key ideas and possibilities afforded by AI, ICT, robots, big data analytics, and IoT must be incorporated into policies at the organizational, national, and international levels.

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