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The Rising Role of Big Data Analytics and IoT in Disaster Management: Recent Advances, Taxonomy and Prospects

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ABSTRACT The recent development of big data analytics (BDA) and the Internet of Things (IoT) technologies create a huge opportunity for both disaster management systems and disaster-related authorities (emergency responders, police, public health, and fire departments) to acquire state-of-the-art assistance and improved insights for accurate and timely decision-making. The motivation behind this research is to pave the way for effective utilization of the available opportunities that the BDA and IoT collaboratively offer to predict, understand and monitor disaster situations. Most of the conventional disaster management systems lack the support for multiple new data sources and real-time big data processing tools that can assist decision makers with quick and accurate results. This paper highlights the importance of BDA and IoT for disaster management and investigates recent studies directed towards the same. We classify a thematic taxonomy with several related attributes and inspect the prevalent solutions to propose a conceptual reference model for the deployment of BDA- and IoT-based disaster management environments. The reference model with its proposed integrated parameters can provide guidelines to harvest, transmit, manage, and analyze disaster data from various data sources to deliver updated and valuable information for disaster management. We also enumerate some important use cases from a disaster management perspective. Finally, we highlight the main research challenges that need to be addressed in such an important field of research.

INDEX TERMS Big data analytics, data sources, disaster communications, disaster management, Internet of Things, reference model, taxonomy.

I. INTRODUCTION

Disasters (natural or man-made) can cause great damage to human life, infrastructure, and environment; anywhere at any time. In the last 10 years, a total number of 3,751 natural disasters such as flood, earthquake, landslide, tsunami, etc. are identified by IFRC, world disaster report 2018 [1]. The financial loss associated with these disasters estimates about 1,658 billion USD, and with human casualties' rising around 2 billion people. Moreover, disastrous events such as terrorist attacks, oil spills, nuclear meltdowns, transportation accidents, etc., are prominent news channel headlines almost every day. Most of the large metropolitan cities of developing nations with increasing population are highly disaster vulnerable regions of the world. This is because their authorities lack situational information in case of a disaster, as they are largely constrained by shortage of resources [2]. Both natural and man-made disasters require preventive and reactive measures that need to be pre-planned for effective applications to reduce the chances of causalities and environmental/infrastructure damage. Therefore, disaster management systems need to effectively extract affirmative knowledge, monitor and analyze the ground situation, facilitate evacuations and predict the occurrence of disasters. Disaster management related government authorities, researchers and practitioners have been endeavoring to enhance the disaster management processes by considering new ideas from various research gatherings, such as

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information technology, cartography, health sciences, and environmental sciences. Their ultimate goal is to enhance the data gathering, managing, processing and visualizing phases of disaster management systems for timely and accurate decision-making. This precise and quick decision-making constraints for the disaster management systems require the utilization and integration of several state-of-the-art technologies to support its operations resourcefully.

With the emergence of latest data analytics, service and communication technologies such as BDA, IoT, cloud computing, fog computing etc., disaster management systems are on the way to get equipped with multiple new supportive data sources as well as fast and cost-efficient data processing tools that can potentially be utilized to assist decision-making in all four phases of a disaster (i.e., rescue, response, mitigation and preparedness). During the course of any disaster, appropriate and timely decision-making based on accurate and up-to-date information determines the effectiveness of a disaster management system [3]. Applications demanding real-time operations on their high-speed data streams require fast and large-scale streaming data analytics to achieve desired results [4]. Through indulging diverse data sources such as physical sensing devices and crowd-sourced information, a larger environment can be provided for disaster management systems to make heterogeneous data sources generate multi-dimensional data useful for performing effective analytics hence generating better results and new insights. The growth of communication through Web 2.0; the possible integration of potential heterogeneous data sources (social media, IoT enabled sensors, satellites, smart-phones, authoritative/public data repositories etc.); and the emergence of the powerful big data analytics tools (Hadoop, Spark, Kafka etc.) with interactive visualization applications (Kibana, Tableau, Plotly etc.) can lead to a paradigm shift in disaster management systems.

The concept of smart city is being widely considered as an ideal solution to attain high-quality collaborative multimedia services [5]. Cities are becoming equipped with the latest digital infrastructure of networks, sensors and smart devices that are generating an enormous amount of data; which can contain rich streams of contextual, spatial and temporal information [6]. Smart city incentives can play a major role in reducing fatalities by providing information and new insights for resourcefully managing the disaster scenarios. With the excessive use of smart-phones and other portable mobile technologies equipped with sensors (i.e., GPS receivers, high-resolution cameras, microphones, accelerometers) the traditional way of data acquisition and management is being challenged. Big sensed data can provide a number of benefits such as, situational awareness enhancement, improved allocation of resources and provision of a better source for informing disaster risk reduction strategies and risk assessments [7]. Multiple data sources can generate a large amount of unstructured data to the remote station on request or after identifying the encompassing activities. However, it is quite challenging to process these huge volumes of heterogeneous data in real-time when a disastrous event is triggered [8]. Practices focusing on the discovery, collection, classification, search and distribution of real-time disaster information have the highest priority for an efficient performance in disaster management tasks [9].

Currently, BDA- and IoT-based disaster management is an under-investigated research area, that includes many interesting opportunities and challenges. With IoT's capability of offering a framework of ubiquitous network with interlinked sensors and smart devices [10], IoT technology possess the potential to be incorporated in disaster management and can provide a positive impact on every phase of emergency response [11]. BDA on the other hand, is known to facilitate the real-time processing of IoT and other related data streams [12], and is capable of providing meaningful results for understanding the situations persisting in the disaster-affected areas, hence based on the analytical results the deployment of resources is optimal and effective [13]. Moreover, big data generated in the IoT environments can be used for performing data analytics, monitoring, forecasts and generating alerts for unusual events [14]. Therefore, we argue that the joint exploitation of BDA techniques and IoT technologies can lead to the development of an innovative, effective and highly-needed disaster management environment. A general illustration of BDA- and IoT-based disaster management environment is demonstrated in Figure.1. The list of abbreviations used in this paper are summarized in their full form in Table 1.

TABLE 1. List of Abbreviations.

ABS	Aerial Base Station
BDA	Big Data Analytics
CDMA	Code-Division Multiple Access
CLOTHO	Crowd Lives Oriented Track and Help Optimization System
CNN	Convolutional Neural Network
CSO	Civil Society Organization
D2D	Device-to-Device
DMS	Disaster Management System
DTSOR	Disruption Tolerant Secure Opportunistic Routing
FINDER	Finding Isolated Nodes using D2D for Emergency Response
FRTN	Flying Real-Time Network
GIS	Geographic Information System
GPRS	General Packet Radio Service
GPS	Global Positioning System
HPC	High-Performance Computing
ICT	Information and Communication Technology
IFRC	International Federation of Red Cross and Red Crescent
IoT	Internet of Things
LAN	Local Area Network
LoRaWan	Long Range Wide Area Network
LTE	Long Term Evolution
MANET	Mobile Ad hoc Network
NGO	Non-Governmental Organization
NLP	Natural Language Processing
PAN	Personal Area Network
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of Service
SMS	Short Message Service
UAV	Unmanned Aerial Vehicle
UE	User Equipment
VCA	Video Content Analysis
VGI	Volunteered Geographical Information
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network

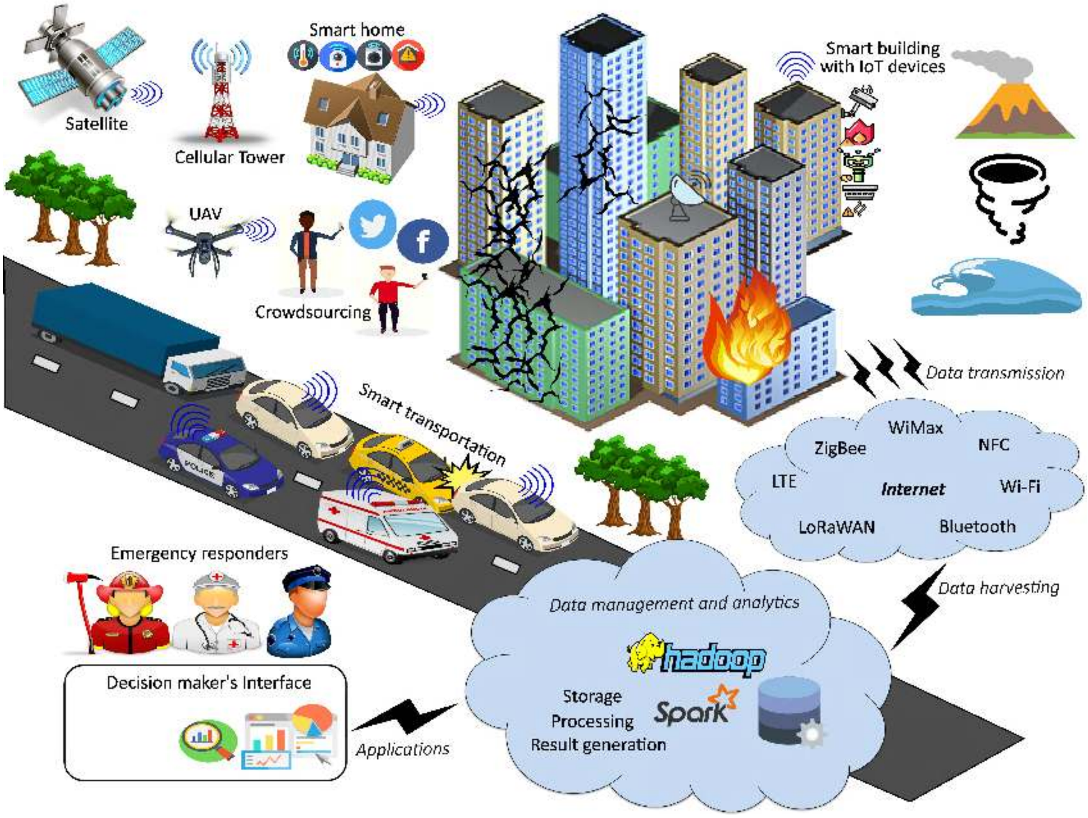

FIGURE 1. General illustration of BDA- and IoT-based disaster management environment.

A. SCOPE OF THIS PAPER

In this paper, we primarily review the existing BDA and IoT literature within the scope of disaster management to explore the unrecognized opportunities and potential challenges associated with their collaboration for effective, timely and accurate disaster management related decision-making. The key forte of this paper is the emphasis that the integration of BDA and IoT technologies can provide promising solutions and new insights for disaster management applications. The aim of this paper is to systematically identify future research openings and contribute to the knowledge of design and implementation of BDA- and IoT-based disaster management environments. This survey paper can assist researchers and practitioners to understand and implement the concepts of BDA and IoT for preparing, responding and recovering from disasters. Concerned authorities for disaster management such as emergency responders, police, public health, fire department, and NGOs/CSOs can benefit from state-of-the-art BDA- and IoT-based disaster management environments to collaborate with each other for effective rescue and response operations. A huge research gap still exists in planning and designing integrated BDA and IoT applications for a time-sensitive and accuracy-demanding application like disaster management. To the best of our knowledge, this paper presents the first survey of its kind regarding BDA and IoT integration encapsulating any disaster management process.

B. CONTRIBUTIONS AND STRUCTURE

The major contributions of this survey paper include:

a) The main benefits and the key requirements of BDA- and IoT-based disaster management environments are identified and discussed.
b) The recent research efforts published with regards to state-of-the-art BDA and IoT for disaster management applications are investigated.
c) A thematic taxonomy is devised to categorize the related concepts and essential parameters while promoting an efficient yet feasible solution for BDA-and IoT-based disaster management.
d) An innovative and comprehensive conceptual reference model for BDA- and IoT-based disaster management environments is proposed with the aim to provide a road-map for future realistic applications.
e) Few credible use cases considering disaster management operations are presented.
f) A set of open challenges that remain to be addressed are highlighted.

These contributions are presented in the rest of the paper as follows. Section II outlines the role of BDA- and

IoT-based disaster management environment by identifying its main benefits and key requirements. Section III presents the investigation of the recent literature on BDA and IoT enabled disaster management. Section IV discusses the devised thematic taxonomy. The conceptual reference model for BDA- and IoT-based disaster management is proposed in Section V. Section VI identifies the use cases, while Section VII highlights the key challenges that need to be addressed. Finally, the conclusion is provided in Section VIII.

II. DISASTER MANAGEMENT AND THE NEED FOR BDA AND IoT

In order to understand the uprising role of BDA and IoT in disaster management, it is important to have a clear image of disaster management systems and its operations. In this section, we will first describe the disaster management systems and its applications and requirements. Then we will discuss the benefits that the collaboration of BDA and IoT offers for disaster management and also identify some of its requirements.

A. DISASTER MANAGEMENT SYSTEMS

Disaster Management can be defined as a systematic approach that involves planning and managing the disaster mitigation, rescue, response and recovery through the collaboration of federal, state, local and private sector entities. The general concept of disaster management can be viewed as a combination of many interrelated processes that aims at providing efficient means to understand, analyze, monitor and predict disaster occurrences. With the rapid advancement in Information and Communication Technology (ICT) from the last two decades, it is now possible to initiate a quick response to any disaster situation in reasonable time and budget.

Disaster Management System (DMS) is a type of information system that assists the decision makers and responders in acquiring, managing and utilizing the disaster information for timely and effective disaster management. The main components of DMS can be divided into data integration, data mining, and multi-criteria decision-making [15]. DMS can be regarded as highly integrated and complex systems that require application specific design and maintenance. Currently, due to the involvement of various interlinked data nodes and with large scale of data requiring real-time analytics, the designing and implementation of a DMS becomes a multidimensional and complex problem. Disaster management applications can be categorized into pre-disaster and post-disaster phases since they deliver diverse functionalities with different requirements for response time, accuracy and effectiveness. Pre-disaster applications such as disaster prediction, early warning system, and simulation exercises etc., focus on measured and inclusive data analysis. On the other hand, post-disaster applications such as Evacuation, Rescue Operations and Monitoring etc., require spontaneous and accurate results. However, each application of DMSs should support heterogeneous and distributed data sources and allow decision makers to extract useful knowledge in an interactive manner. DMSs must possess the desirable technical factors such as reliability, availability, maintainability, accuracy and usability requirements [16]. As categorized in Table 2 each DMS application needs to satisfy the requirements. Through ensuring these requirements the developers can set benchmark quality attributes to verify the performance and measure the effectiveness of the DMS.

TABLE 2. Main DMS Applications and Requirements.

Disaster Status	DMS Applications	DMS Requirements
Pre-disaster	Disaster Prediction Early Warning Simulation Exercises	Reliability Availability Maintainability Accuracy Usability
Post-disaster	Evacuation Rescue Assistance Monitoring / Surveillance Logistics Management	

B. BDA- AND IoT- BASED DISASTER MANAGEMENT ENVIRONMENTS

Disaster management systems requires to be shifting to state-of-the-art environments that are supporting multiple data sources and are equipped with latest technologies offering broader range of capabilities for enhanced connectivity, storage, real-time analytics and cost-effective applications. These environments can be successful deployed by indulging BDA and IoT technologies together for disaster related operations. Figure.2 presents the benefits that can be achieved through the combination of BDA and IoT for disaster management systems and also identifies the main requirements for deploying a BDA- and IoT-based disaster management environment.

1) BENEFITS

BDA- and IoT-based disaster management environments can provide a number of benefits within the scope of disaster management. Some of the key benefits are described in the following subsections.

a: CONNECTIVITY

Connectivity is required to facilitate the aggregation of huge volumes of data from heterogeneous data sources to high-performance computing infrastructures and further sharing of information with concerned disaster management authorities. Due to the availability of various communication technologies, one of the key benefits of BDA- and IoT-based disaster management environment is to provide reliable connectivity. Connectivity among the interlinked data nodes and DMS acts as the backbone for the insurance of successful operations. As a number of communication technologies are available the overall environment architecture has to be flexible to deal with different communication protocols including local and remote communications [17]. Moreover, with the evolution in post-disaster communication networks, seamless

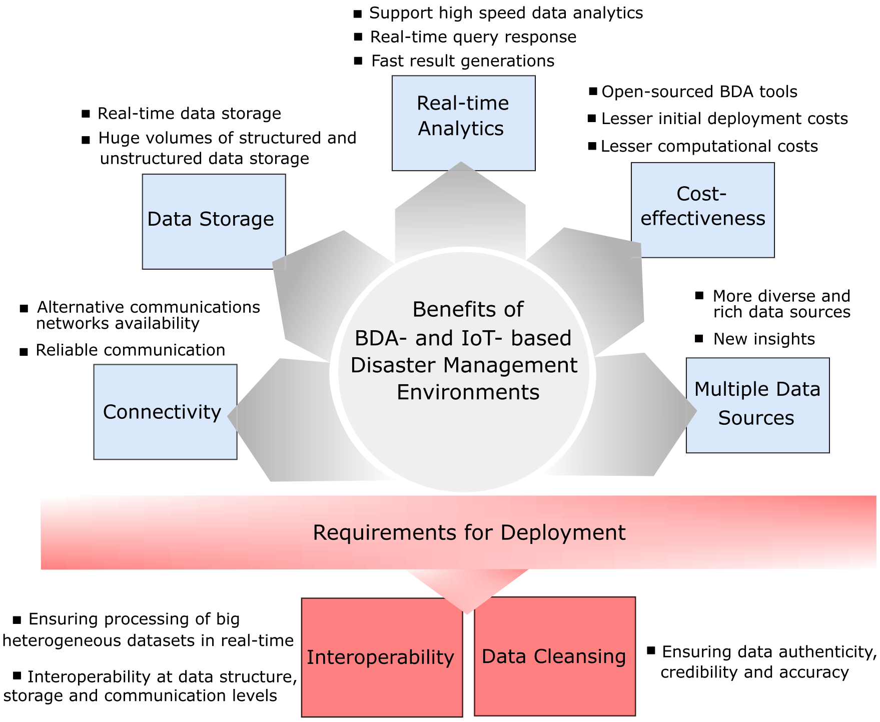

FIGURE 2. Benefits and Requirements of BDA- and IoT-based Disaster Management Environments.

connectivity is provided even with the distraction of other conventional communication networks in post-disaster situations.

b: DATA STORAGE

Storage of huge volumes of heterogeneous data in real-time can be challenging in conventional DMSs. With BDA technologies such as Hadoop, large-sized structured or unstructured datasets can effectively be stored on low-cost commodity hardware. Real-time environments having streaming storage capability for IoT devices and other data sources can enhance the entire data processing efficiency and can provide a number of benefits to the designated applications [18]. Moreover, BDA technologies can enable efficient processing with low latency for data analytics while maintaining the storage of massive unstructured datasets.

c: REAL-TIME ANALYTICS

Due to the dynamic and demanding nature of disaster management, real-time analytics is one of the key requirement for current disaster management environments. Connectivity among various data sources results in massive data generation at high speed that can create hurdles in performing real-time analytics. A dedicated technological platform with the software solution capability to perform real-time processing, streaming and in-memory computing is needed to deal with such enormous and high-velocity data [19]. The ability provided by BDA to perform fast analytics with real-time queries is vital to help decision makers obtain required results for an effective emergency response.

d: COST-EFFECTIVENESS

BDA tools are mostly open-sourced and it offers a huge cost reduction opportunity as compared to buying proprietary data processing software solutions for disaster management operations. Cost-effectiveness is an important factor for disaster-concerned authorities in developing countries, where disaster management systems are not deployed due to lack of funds. Map-reduce is an ideal solution for cost-effective data storage and useful for decreasing the computational costs of the overall system [20]. Moreover, with the declining costs of hardware and software utilities of IoT deployments, state-of-the-art technologies can be deployed easily with much lesser budget.

e: MULTIPLE DATA SOURCES

In the context of integrating IoT environments equipped with multiple data sources such as cameras, sensors, smartphones etc., with BDA technologies assisting in data processing, a number of data sources can be incorporated to gather new and valuable insights and information. Engaging multiple data sources provide alternative ways to address problems that require multidimensional representations of the data to extract the common patterns for a solution that are inaccessible through a single source of data [21]. With the availability of diverse and rich data sources, BDA- and IoT-based disaster

TABLE 3. Comparison between recent BDA-based studies focusing on disaster management.

Study	Year	BDA Tools	Data Source	Text Analytics	Spatial Analytics	Focus
[24]	2018	Spark	Crowdsourced sensor data	✓	✓	Improving near-real-time application for flood risk management
[25]	2018	Kafka, Spark	Twitter	✓	✓	Providing disaster situational-awareness
[26]	2018	Spark	Historical database of meteorological data center	✓	✓	Simulation for Typhoon risk assessment
[27]	2018	Spark	Historical database of earthquake catalogs	✓	✓	Earthquake magnitude prediction
[28]	2018	Kafka, Spark	Mobile communication base station data	-	✓	Identifying earthquake emergency through high precision heat map
[29]	2017	Hadoop, Spark	Satellite Imagery, Sensor data	-	✓	Fire response optimization and evacuation planning
[30]	2017	Hadoop	Social media, Remote sensing, Wikipedia data	✓	✓	Enhancing disaster coordination and assistance for relief operations

management environments can surpass conventional DMSs data sources.

2) REQUIREMENTS

The key requirements for deploying BDA- and IoT-based disaster management environments are described in the following subsections.

a: INTEROPERABILITY

The capability of being able to link, combine and process two or more datasets is known as interoperability. The collected datasets from heterogeneous sources might not align with each other, or it can be difficult to determine the possible relationships among them. During real-time data harvesting and integration, it is important and challenging at the same time to achieve the maximum level of interoperability. Interoperability can be ensured at technical, syntactic, semantic and pragmatic levels [22]. Hence, good practice can be to apply interoperability checks at the data structure, storage, and communication levels through abstraction and virtualization to ensure high reliability.

b: DATA CLEANSING

Data cleansing is essential for disaster management, as incomplete, error-prone and ambiguous data can lead to more problems and wastage of precious time. Data cleansing parameters determine the accuracy of the analysis carried out on a particular dataset. However, as data cleansing works on a complex relationship model and can require extra computation power and processing time, a balance should be kept between the data cleansing model and the accuracy improvement of the analysis [23]. Moreover, with the growing usage of social media data for disaster management processes, a different kind of unstructured data is emerging that needs to be checked for authenticity, credibility, and accuracy.

III. RECENT ADVANCES

The research on BDA and IoT in the domain of disaster management is still in its infancy. This section reviews the recent research contributions with the aim to identify the key research areas and highlight the latest advancements recognized to enhance the disaster management related processes.

A. BDA FOR DISASTER MANAGEMENT

Big data analytics provides a variety of solutions on huge multi-sourced datasets collected from the disaster area to uncover hidden patterns and understand the situations on the ground so that rescue activities can be carried out effectively and logistics can be managed optimally. One of the main advantages of using BDA is that it enables data scientists to analyze huge volumes of data involving different data sources that may not be collected using traditional tools [31]. BDA depends on various technologies and tools for the execution of huge volumes of structured, semi-structured and unstructured data for analytical processes. Research trends in BDA for disaster management focus on both the content/text and the spatial points of view of the data for analysis and result generations [13].

Despite the limited publications regarding BDA for disaster management, some of the recent research as compared in Table 3 shows that a variety of data sources are being utilized with various open-source BDA tools within the scope of disaster management. For instance, for flood risk management an interoperable mechanism was designed by authors in [24] to integrate heterogeneous sensors that enable access and filtering of the data in near-real-time using Spark. The approach used in their study offers a method to enhance near-real-time applications using heterogeneous data streams i.e., crowdsourced and sensor data. In another study [25], a big data crisis mapping system was designed that is able to collect and analyze Twitter data utilizing Kafka and Spark. The system extracts information related to the disaster from the collected geo-tagged tweets by applying classification technique and semantic annotators. This information is then visualized on a web-based dashboard for emergency responders to acquire greater situational awareness in the early stages of the disaster. The authors in [26] specified that Spark-based computation on huge sets of historical data provides better performance for the simulation to identify typhoon risk assessment feasibility. Similarly, in another study [27], the authors used several regression algorithms using Spark to analyze large catalog of earthquake events. They demonstrated very promising results regarding the prediction of earthquake magnitudes in the state of California. In [28], the authors proposed a real-time collection and classification algorithm of mobile phone position data by stream processing environments such as Kafka and Spark to produce a high precision heat map of the population affected by the earthquake. An integrated disaster management system developed through the combination of Hadoop and Spark was presented in [29]. Their proposed system addresses large-scale datasets issues of spatial and temporal perspectives and provides predictive risk analytics for fire response's resource optimization and evacuation planning. A study was conducted [30] to demonstrate a framework that synthesizes multi-sourced data such as social media, remote sensing and Wikipedia to build a flexible solution that provides historical and future disaster analysis involving Hadoop for spatial data mining and text mining.

B. FROM WSN TO IoT FOR DISASTER MANAGEMENT

Wireless Sensor Networks (WSNs) consists of autonomous low-powered sensors nodes that are spread across a specific area and capable of measuring and reporting of environmental conditions (i.e., smoke, temperature, vibration, locations). WSNs have long been used in disaster monitoring related research, such as event monitoring in emergency scenarios [32], natural disaster monitoring [33], and multi-agent system-based disaster management [34]. However, unaided WSNs lack in a multitude of social, technical and economic perspectives for extensive deployment in disaster management [35]. WSN is an integral part of IoT and can benefit from the data management, processing and decision-making characteristics of IoT to provide meaningful interpretations and supporting decisions based on its generated sensed data. From the last few years, research interest in many domains including disaster management is diverted to IoT, as it is predicted that by 2020, IoT will be interconnecting nearly 50 billion new connections [36]. IoT provides a resourceful platform, consisting of various tools and technologies that are supported by communications among various physical and virtual entities to observe, communicate and process data. IoT provides an ideal solution for data gathering in disaster-struck areas, as it offers alternative means of communication carried on low battery-powered and IoT-enabled wireless devices.

Recent research on disaster management is widely considering IoT to provide multi-dimensional and multi-sourced information for timely decision-making. IoT can be effective solution for disaster event detection. IoT offers smart aggregation, integration, and analysis of multi-dimensional and multi-sourced data, which are the main steps for situational awareness for effective decision-making. In a study [37] the authors demonstrated how IoT with semantic web technologies can be successfully deployed for earthquake-related event detection. The proposed system was able to semantically annotate streams that were retrieved from web services gathering IoT-based sensors data for effective earthquake event detection. Another system based on IoT [38] focused on the quick and systematic evacuation of large crowds of people after disasters. Crowd lives oriented track and help optimization system (CLOTHO) aims at reducing the loss of lives by deploying an IoT-based solution that uses a mobile cloud computing platform. The data collection part of the system includes the mobile terminal that is backed by IoT while the storage and data analytics part comprises of a cloud-backed system. Ben Arbia, *et al.* [39] proposed an emergency and disaster relief system which is monitored by a cloud-based IoT platform. The system is known as Critical and Rescue Operations using Wearable Wireless sensors networks (CROW^2) and integrates heterogeneous wireless devices such as smartphones and sensors with various communication technologies such as WiFi and Bluetooth to support end-to-end network connectivity. This system helps emergency rescuers to be connected with any functioning network or the internet.

C. POST-DISASTER COMMUNICATION NETWORKS

Most of the conventional communication infrastructures get unresponsive in post-disaster scenarios, either due to physical damage or overloaded network congestion. Recent advancements in wireless communication technologies have a lot to offer for post-disaster communications with rapidly deployable, scalable and efficient networks that can ensure the flow of data and provide communication assistance for rescue and response operations.

Device-to-Device (D2D) communication offers an improved Quality of Service (QoS) and high Quality of Experience (QoE) for User Equipments (UEs) to manage radio spectrum and most importantly energy consumption of the devices in the disaster-affected area. A disaster communication architecture based on D2D communication was proposed in [40]. The study has focused on extending the lifetime of energy-constrained networks by employing energy harvesting techniques from radio frequency signals via the base station at the user equipment relay. Similarly, another study [41] focuses on cooperative D2D protocol to ensure smooth connection and expand the average battery life of the devices. The protocol was designed to assist low battery level devices to find neighboring devices having high battery levels so that they can act as relay. This mechanism is aimed at extending the communications for covering the disaster area. In [42], a framework named FINDER (Finding Isolated Nodes using D2D for Emergency Response) was proposed to locate and link the disconnected mobile devices in the disaster area. The study uses a multi-hop D2D communication derived from Ant Colony optimization to improve the message deliver probability and to extend the network lifetime and energy efficiency of the devices.

A MANET can be defined as a temporary distributed network that comprises of a set of mobile nodes with infrastructure less, decentralized and dynamic features. MANETs can provide a practical solution for post-disaster communications. The researchers in [43] reviewed the mobility models, routing algorithms and network simulators for MANETs in disaster scenarios. For post-disaster scenarios, the authors in [44], introduced new schemes for MANETs routing and gateway load balancing. This novel scheme aims at improving communications in affected areas by reducing network congestion. A novel framework named disruption tolerant secure opportunistic routing (DTSOR) was proposed in [45] that ensures smooth and secure communication between high mobility devices during emergency situations. Through performance analysis and simulations, the study claimed that the proposed framework in terms of the packet delivery ratio, network overhead and throughput overtakes many modern data transfer approaches. Another study [46] proposed the concept of hybrid cellular-MANET architecture using available cellular base stations in post-disaster situations. The proposed architecture is responsive to device mobility and possesses the self-organizing feature of MANET.

UAVs provide an open opportunity for quick and easy deployment of cellular base stations as secondary communication infrastructure where required in post-disaster scenarios. For distributing tactical and sensor data over a specific area or connecting on ground devices within range, the data link system of UAVs can be programmed effectively with additional broadcasting jobs. The authors in [47] reviews the latest advancements in UAVs for network-assisted post-disaster management. They identified the key issues and suitable network architectures for UAVs assisted network for disaster management. A study was conducted [48] to investigate the use of UAVs as Aerial Base Stations (ABSs) for disaster communications in a situation where conventional communication infrastructures have totally failed. The study analyzed communication improvements obtained by the ABSs through simulations and found a noticeable increase in effective communication probability when ABSs were deployed in optimal locations. A flying ad-hoc network, named the Flying Real-Time Network (FRTN), was proposed in [49]. The feasibility of this proposed network to provide communication in post-disaster scenarios was presented by illustrating the real-time scheduling of message delivery and simulation-based analysis.

D. CROWDSOURCING

Crowdsourcing is boosting the idea of "people as sensors", a concept recently being recognized in the disaster management domain for incorporating new and big datasets that can be processed for retrieving required information with more insights. Crowdsourcing can either be active, where people willingly participate to provide data; or passive, where typically social media platforms are used to collect the data with or without the contributor's knowledge. Active crowdsourcing platforms are deployed by concerned authorities (Government or NGOs/CSOs) to acquire real-time information from disaster-affected people, for improving emergency response and resource allocations. There are a number of web-based and mobile applications for enabling active crowdsourcing in a disaster-affected area. One such platform that facilitates real-time, multimedia supported and collaborative mapping is Ushahidi [50]. Ushahidi platform has been extensively utilized in disasters such as the 2010 Haiti earthquake and the 2011 Japan tsunami. Active crowdsourcing provides more credible data with less noise as compared to data collected from passive crowdsourcing that require different data quality filtrations. However, most of the recent research efforts are focused on passive crowdsourcing for disaster management; as big volumes of data are generated with people tending to report a status/tweet/description, image, video/audio and most importantly precise locations using various social media platforms. This massive data contains critical information (text, image or video), sentiments, personal opinions, and GPS coordinates. Effectively analyzing such data can provide a better situational awareness and enhanced assistance for rescue and response. Moreover, social media offers a suitable solution for establishing communications with affected people, acquiring feedbacks and enhancing empowerment between people and concerned authorities.

Recently social media is one of the most emerging big data source for disaster management research. Particularly, with the increasing use of smartphones in the last few years, geospatial data generated from social media platforms are more in demand over conventional data sources for disaster management [51]. The concept of Volunteered Geographical Information (VGI) [52] is being widely used for disaster management, as citizen engagement in disaster response is increasing. Kusumo *et al.* [53] examined the benefits of using VGI for spatially planning the evacuation shelters. They used Jakarta floods as a case study and their analysis showed that 35.6% of the shelter locations desired by residents matched with the locations of the government evacuation shelters. In another study [54], VGI extracted from social media was used for real-time rainfall and flooding events detection through user-generated high-quality eyewitnesses in shape of texts and photos by applying deep learning approaches. Flood events in various cities such as Paris, London and Berlin were targeted as case studies and analysis was performed through spatio-temporal clustering and visualization techniques enabled by a web map application.

As mentioned earlier, the reliability of passive crowdsourced data has been difficult to evaluate. Limited research is available until now in terms of quality assessment methods on the data produced by social media platforms. One such study [55] on the credibility assessment of users reporting about various disasters, compared the user profiles and their geographic references, with the classification of tweets through Naive Bayes models. The datasets of this study were extracted from past earthquake events in Myanmar and Italy. The study found similar geographic granularity and identified 88 to 99% precision of information contained in the

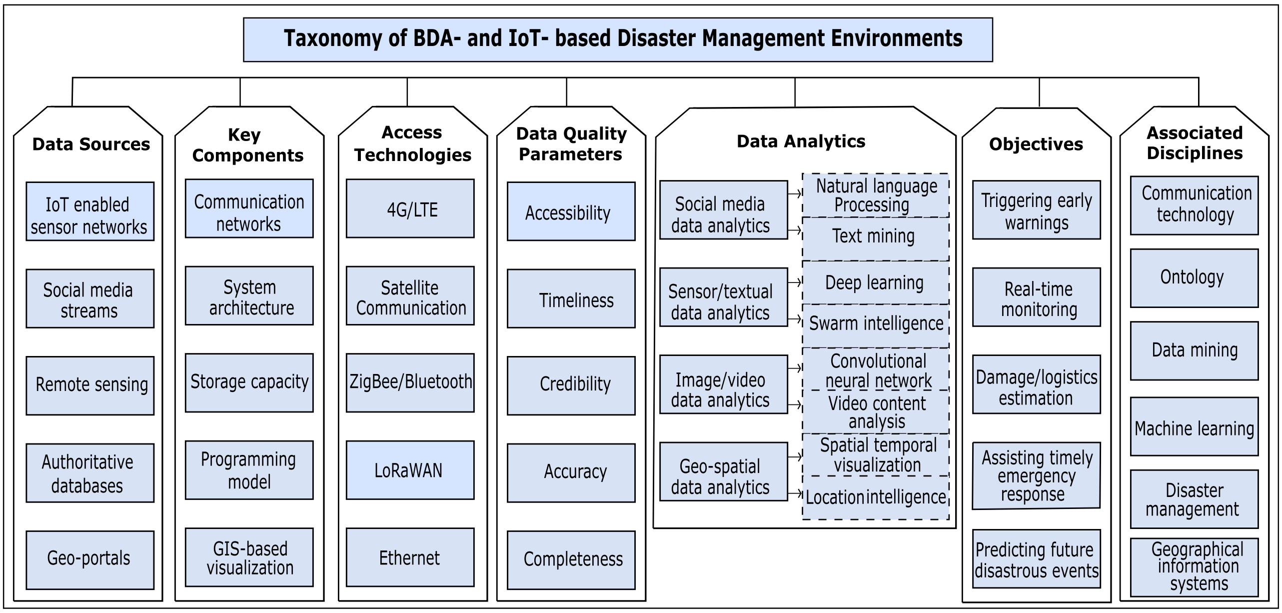

FIGURE 3. **Taxonomy of BDA- and IoT-based disaster management environments.**

collected Tweets. The need to effectively extract meaningful information from huge sets of data generated by social media platforms in a lesser amount of time for effective disaster management is an emerging issue. BDA seems to be the choice in the recent research efforts to deal with such issues. The authors in [56] used Hadoop platform and machine learning techniques to perform sentiment analysis on big social data. Support vector machine algorithm was used for the sentiment classifications and an interactive visualization mechanism was deployed to provide information for prompt decision-making.

IV. TAXONOMY

In this section, we present the thematic taxonomy of BDA- and IoT-based disaster management. The taxonomy identifies and categorizes key attributes essential for the development of BDA- and IoT-based disaster management environment. For the development of this taxonomy, we followed an iterative approach as suggested by Nickerson *et al.* [57]. Due to the involvement of multi-disciplinary topics i.e., Big Data Analytics, Internet of Things and Disaster Management, we had to consider different dimensions and characteristics that are important to identify and valuable for the development of BDA-and IoT-based disaster management environments. The development of this taxonomy was a continuous process, involving refinement at various stages to sufficiently satisfy the qualitative attributes of being, (a) concise (a limited number of dimensions that are important, because extensive classifications are difficult to understand), (b) comprehensive (includes all main dimensions of objects of interest), (c) extendable (open to include new dimensions), (d) explanatory (provides valuable descriptions of the nature of the objects under study) [57]. This thematic taxonomy was classified by conducting an extensive and inclusive review of the related literature, with the aim to unearth the main attributes of BDA- and IoT-based disaster management environments. In this effort to capture the vastness and variety of multi-disciplinary topics involved, we identified some of the key attributes on the bases of their significance, consideration and association with BDA- and IoT-based disaster management environments. This taxonomy can provide guidance to researchers to understand the foundations for the development of such environments and future acquisitions. As illustrated in Figure.3, the taxonomy at the top level is categorized into the following seven attributes,

A. DATA SOURCES

The key characteristic of BDA- and IoT-based disaster management environment is its diverse and rich data sources. Table 4 presents the details of potential data sources for disaster management. The main potential data sources include social media streams, the integrated networks of IoT enabled sensors, remote sensing, authoritative or public historical databases and geo-portals. The data generated from these sources is of diverse descriptive nature (i.e., location, temperature, humidity, orientation, event description, image, audio/video etc.) and hence involves different data formats. Moreover, most of the data captured are unstructured and require some pre-processing techniques prior to any kind of analytics. It is very important to understand the significance of disaster-related data, that needs to be accessible, accurate and complete, and also support real-time processing. The main challenges associated with disaster-related data are:

- Identifying and aggregating disaster-related heterogeneous data from IoT/big data infrastructure.

TABLE 4. Summary of data sources.

Data Source Category	Potential Data Sources	Available Information	Possible Data Formats	Data Structure	Data Processing Type
Social media	Twitter, Facebook, YouTube	Text, Image, Audio/Video	JSON, CSV, JPEG, MPEG-2	Unstructured	Streaming
IoT-enabled sensors	Surveillance cameras, Seismometer, Thermometer, Hygrometer	Status data, Location-based readings	JSON, GeoJSON, XML, CSV, MPEG-2	Semi-structured	Real/near real time
Remote sensing	Satellite imagery, UAV imagery	Aerial imagery, GPS measurements	IMG, GRID, GeoTIFF	Semi-structured	Batch
Historical data warehouses	Government, Humanitarian/ NGO's Databases	Demographic, Health records, Recorded maps, Digital archives, Surveys	CSV, GFF, XML, JSON	Structured	Batch
Geo-portals	National Geo-Portals, Open Global Geo-Portals	Spatial Data	KML, SHP, GeoJSON, TIN, OSM	Structured	Batch

- Extracting useful information from huge volumes of collected heterogeneous and unstructured data, that requires data pre-processing and event detection techniques.
- Interpreting and visualizing data in near real-time.

B. KEY COMPONENTS

The realization of a BDA- and IoT-based disaster management environment depends on the availability of some critical components. Communication networks are one of the key components and act as a backbone in developing the environment. A combination of various communication networks and protocols provide the overall network infrastructure for data transmission and facilitate connectivity among numerous data sources. Disaster information networks should be assembled by combining various wired, wireless and satellite network so that a ''never-die-network'' can be ensured for both normal and disaster occurrence cases [58]. System architecture provides the blueprint that determines the overall structure and behavior of a system. A well-designed system architecture is a cornerstone to tackle the conceptual and practical issues that can be faced with a complex system involving big data and IoT. A pre-planned conceptual model provides well-thought-out solutions for the successful integration of heterogeneous components for an accurate and effective disaster management application. Due to data acquisition from heterogeneous sources at a rapid rate, the need for effective data storage and management of these huge datasets is obligatory, while ensuring availability and reliability at the same time. The main challenge is to differentiate and store large-sized data (i.e., images and videos) accessed in the real-time, from the small-sized data (i.e., log and text files) accessed in batches, acquired from sensors and static databases. Programming model represents the core characteristics of any big data framework and plays an important role in determining the performance of big data processing engines. It is important to select a programming model that functions in real-time with high performance and reliability. There are various programming models currently available, i.e. MapReduce, SQL-based, functional and statistical models having different advantages and applications. In any disastrous situation, emergency responders and decision makers require quick and accurate location-based descriptions, suggestions and predictions easy to understand and interact. GIS-based visualization tools provide a user-friendly and interactive interface for mapping datasets that can demonstrate the overall picture and offer new insights to the decision makers.

C. ACCESS TECHNOLOGIES

A reliable, robust, energy efficient and disaster resilient data transmission network acts as the backbone for any disaster management system. Access technologies from a disaster communication perspective should provide reliable connectivity and optimized services for effective data transmission between data generating devices and back-end servers.It is very important to ensure the flow of data and the safety and connectivity of the network in order to acquire situational awareness in case of a disaster event [59]. A collection of various communication network topologies is required to obtain an autonomous BDA- and IoT-based disaster management environment. Some of the main access technologies that are useful for disaster communication are 4G/LTE, satellite communication, ZigBee, Bluetooth, LoRaWan and Ethernet. LTE (Long Term Evolution, also called 4G) provides communications with wide area mobility, improved interactivity and on the go multimedia services. 4G/LTE technologies are widely used by major telecom operators globally. With its high speed and low latency features users are able to operate applications such as social networks, maps navigation, browsing, etc. in addition to traditional voice calls and SMS services. These cellular mobile communications with its wide access to the people can be utilized for early warnings and disaster alerts. Satellite communications are not vulnerable to damage from disasters, which make them the reliable communication infrastructure in full-fledged disasters. However, the main concerns are the cost of satellite bandwidth, low throughput and large latency. Nevertheless, satellite communications can be a cost-effective solution for sever disaster than establishing a new communications infrastructure in disastrous areas. Short-range wireless technologies such as ZigBee and Bluetooth can be effective in establishing communication networks within a small disaster-affected area. LoRaWAN is emerging as the new communication technology for smart city applications. LoRaWAN ensures interoperability between various operators and offers low-power and low-cost mobile communications that can be beneficial for disaster communications. The importance of wired communication technologies (i.e., Ethernet, PSTN) cannot be neglected in disaster communication networks. High-speed communications can be achieved with dedicated fiber-based connection lines to enable transmission of data within the Local Area Networks (LAN) of various disaster management authorities.

D. DATA QUALITY PARAMETERS

Incomplete, ambiguous, error-prone and noisy data can cause serious issues in data analytics and hence in decision making for disaster response. Data quality parameters determine the accuracy and productivity of the analysis performed on a particular dataset. Data quality dimensions such accessibility, timeliness, credibility, accuracy and completeness are vital for disaster management processes. Accessibility determines the mode in which the data is accessed from the source and whether the data has any legal constraints on usage. Timeliness describes the movement of data, i.e., real-time or static and whether the data needs to be updated. Credibility is to ensure that the data is verified and its source is identified. Accuracy is to check whether the data is free of any redundancy and is explicitly related to the scenario. Completeness determines the clarity and understandability of the data according to the situation.

E. DATA ANALYTICS

The state-of-the-art big data analytical tools are one of the key technologies that assist the concept and operation of the BDA- and IoT-based disaster management environments. The heterogeneous data sources, producing huge volumes of multi-dimensional and multi-modal data requires powerful data analytics for productive execution. To develop an efficient and real-time data execution enabled system for disaster management processes various big data analytical tools need to be employed. A combination of advanced big data analytical tools, i.e., Hadoop Ecosystem and Spark can be utilized to analyze huge sets of data accurately and efficiently with suitable algorithms and techniques. Data analytics varies according to the data types captured from the heterogeneous data sources and the desired results. Following are some data analytics types and prescribed methods that can provide new insights and quick results for effective rescue and response based decision-making.

1) SOCIAL MEDIA DATA ANALYTICS

With the extensive use of social media applications, users in real time generate huge amounts of unstructured but potentially useful datasets. These datasets need to be checked for reliability, credibility, and authenticity prior to any kind of analytics aimed at extracting actionable information. Sequenced information processing operations i.e., filtering, categorizing, extracting and summarizing can be the best approach to deal with these issues [60]. Natural Language Processing (NLP) techniques can be used to search, classify, and compile textual descriptions acquired from social media user in a disaster response scenario [61]. Text mining is another useful analytic technique to extract valuable structured data from huge volumes of unstructured text. Social media datasets can be evaluated with a number of standard text mining techniques to collect the required information about a specific disaster [62]. Text mining basically regulates semantics, keywords, labels, tags, and themes in the shape of separate files and formats for extracting key pieces of information.

2) SENSOR/TEXTUAL DATA ANALYTICS

Another data source generating huge volumes of data is IoT-based sensors. These big sensed datasets play a vital role for making spontaneous and effective decisions for disaster rescue and response. The function specific and geographically distributed sensors can provide valuable information and insights through powerful analytics. Deep learning algorithms operate on hierarchical learning process to extract high-level and complex abstractions as data representations. Deep learning is an important big data analytics tool as it effectively analyses huge amounts of unsupervised data even being unlabeled [63]. IoT-based sensors are complex to manage and aggregating data is hard usually due to the lack of decentralized control. Swarm intelligence can be useful to resolve complex issues with IoT-based sensor systems having dynamic properties and limited computation power [64].

3) IMAGE/VIDEO DATA ANALYTICS

The real-time streams of high-quality images and video content, from surveillance cameras, UAVs and citizens with mobile devices are providing decision-relevant situational information on causalities and damaged buildings, roads, bridges, etc. With the advances in machine learning and vision techniques for analyzing image/video datasets, rescue operations, planning evacuation routes, damaged infrastructure surveys, and other disaster management activities can be greatly assisted. Convolutional neural network (CNN) is a class of deep neural networks, commonly used to extract topological properties from visual imagery. It is simple and robust to operate, as it automatically learns visual feature sets from the training data. A study [65] on investigating the potentials of CNN for aerial imagery demonstrated that CNN are useful for object detection and correctly locates the areas that match to categories in which the CNN was trained for. Moreover, [66] used CNN on video analysis for fire detection and concluded that CNN achieves better classification performance than some of other conventional methods for fire detection. Video content analysis (VCA) enables automatic video analyzing to search, identify, classify, and determine temporal and spatial events. Using video content analysis, [67] proposed a warning system for flood event detection on feeds from surveillance cameras.

4) GEO-SPATIAL DATA ANALYTICS

Geo-spatial data or data with location component is considered as the most essential input element in latest technologies. The geo-spatial data-sets needs to be analyzed to gain information about disaster locations as it occurs, identify the area and people that require urgent assistance and locate appropriate areas for shelters to name the least. With the advent of satellite remote sensing, location-based sensors and smartphones equipped with GPS, a huge volume of geo-spatial data is generated. Spatial temporal data visualization comprises of powerful tools that supports analysis of geo-spatial data over time through interactive visualization. Spatial-temporal data visualization greatly assists decision-making in all the phases of disaster management [29]. Location intelligence offers unique insights, reveal hidden patterns and information based on geo-spatial data for better decision-making. Location intelligence is effectively used to detect the spatial and temporal distribution of flood risks [68] and for waste collection solution to improve cities management systems [69].

F. OBJECTIVES

The convergence of BDA and IoT technologies can set a new meaning to the overall objectives of disaster management. One of the main objective of this system is early warning generation, that can save lives and reduce infrastructure damage. Real-time disaster monitoring involves the extraction of information from the system to make informed and timely decisions. It is important for the system to accurately estimate the damages caused and logistics required. Moreover, it should figure out the evacuation routes quickly in emergency response. Effective and timely decision-making needs a reliable, fast processing and data resourceful system that integrates different state-of-the-art technologies to improve its operations. Predicting future disastrous events is becoming a reality with the evolution in the latest technologies, such as low-powered sensor networks, reliable wireless technology, sophisticated algorithms and advanced data analytics.

G. ASSOCIATED DISCIPLINES

It is important to identify and merge the concepts of all the related disciplines that are used to design, develop and manage BDA- and IoT-based disaster management environment. The general perception that BDA and IoT-based environments only requires technical skill is wrong, as interdisciplinary approaches are required in their domain-specific applications. Professionals having a specific set of skills and experience of communication technology, data mining, machine learning, ontology, disaster management and geographical information systems need to collaborate in designing an operational architecture that can fulfill the objectives of BDA- and IoT-based disaster environments.

V. REFERENCE MODEL

As discussed, the integration of BDA and IoT technologies can provide a resourceful platform for acquiring, storing, processing big disaster-related data and generating the required results for timely and accurate decision-making. To effectively utilize the value-added capabilities and opportunities offered by BDA and IoT within the scope of disaster management, we introduce a novel reference model derived from the classified taxonomy and related literature. Based on the identification and abstraction of correlated technical and theoretical knowledge, this novel reference model presents the overall functionality and configuration for disaster management environments. The main theme of this reference model is to provide guidelines for developers to ensure effective decision-making through such disaster management environments. Multiple IoT based BDA architectures focusing on general applications are found in the literature [70] [71] [72] [73]. Most of these architectures are focusing on overall operations in a smart city concept and there is a lack of disaster management specific architectural models in the existing literature. Feasibility of defining a standardized framework that deploys IoT and BDA for time critical and performance demanding application like disaster management is far from reality. However, it is theoretically feasible to direct the designing process in this new and dynamic environment towards the deployment of a realistic architecture.

For designing the proposed reference model, this study has adopted design science research method [74] to present the high-level model for an environment where the integration of potential big data sources and operations of various tools and techniques can ensure effective disaster management. This study followed the seven design science research guidelines i.e. "*Design as an Artifact, Problem Relevance, Design Evaluation, Research Contribution, Research Rigor, Design as a Search Process, and Communication of Research*" specified by Hevner, *et al.* [75]. The proposed reference model is an artifact that utilizes big data analytics and IoT for effective disaster management (*Design as an Artifact*). The model supports processing huge sets of heterogenous data (structured/unstructured) in real time that is highly demanded by current disaster management systems (*Problem Relevance*). The implementation of different components in the proposed model can be justified by numerous performance measures published during actual deployments (*Design Evaluation*). The innovative design that assembles various data sources and the integration of state-of-the-art artifacts for effectively utilizing the benefits that can be gained through BDA in real-time for disaster management is the key contribution of this study. Moreover, this research highlights new challenges and parameters when deploying IoT and BDA in disaster management (*Research Contribution*). This study relies on a systematic literature review on the advanced topics of IoT and BDA for disaster management. The formation and assessment of the artifacts are established from the recognized knowledge base from multiple academic fields

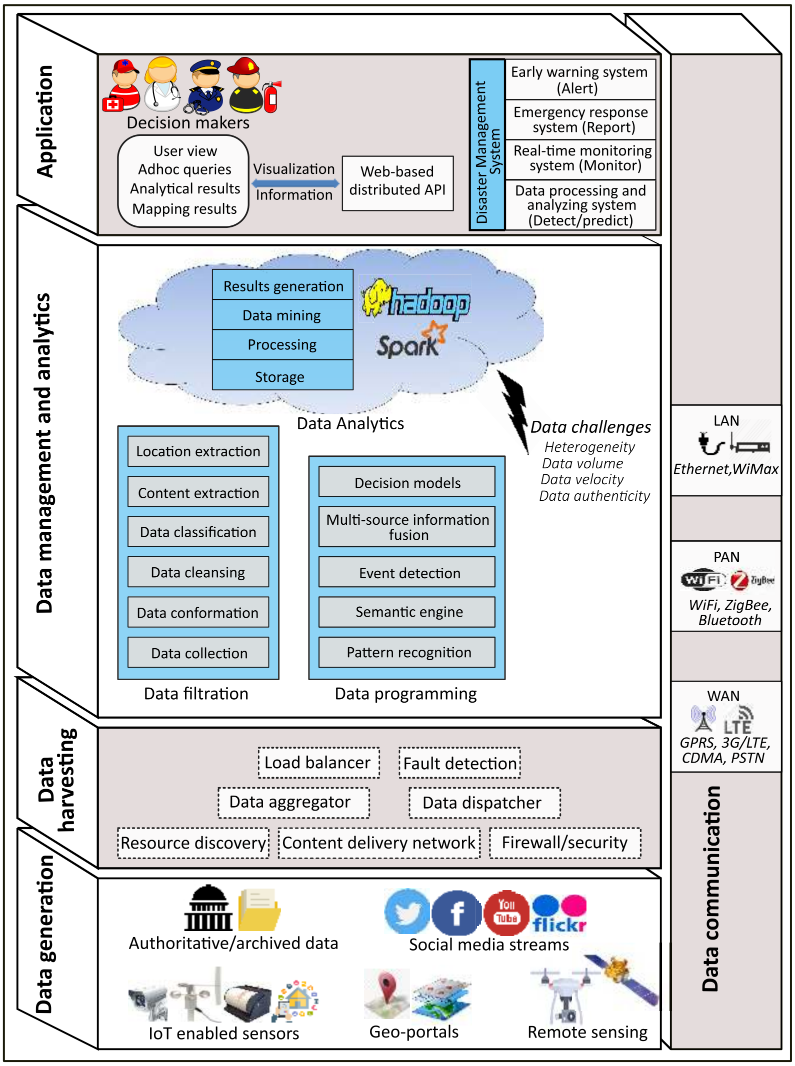

FIGURE 4. The proposed BDA- and IoT-based disaster management reference model.

(*Research Rigor*). Critical feedback and continuous literature study were carried out throughout the design of the framework, which led to many iterations and modifications (*Design as a Search Process*). Involving both the linked academic community and related field professionals to highlight any defects in the final design resulted in more improvements (*Communication of Research*).

Moreover, after thorough analysis of several related architectures, we found out that the following key points need to be considered during the design process of any disaster management environment that is involving BDA and IoT technologies.

- The architecture needs to be scalable to indulge new data sources that can provide valuable information and insights.
- Flawless communication over the network or alternative networks in case of any transmission failure or destruction.
- Effective storage of structured and unstructured data that are either collected through real-time streams or historical data batches.
- Flexible to accommodate various computation intelligence techniques, algorithms and analytical packages.
- Able to share the results to other systems or applications and present the information in an interactive manner to the decision-makers.

The design of some disaster management environments may vary depending on its application scope and size (i.e., industrial/building disaster management vs urban disaster management) and the nature of required results based on urgency, performance, compatibility and scalability. However, this reference model can provide a standardized framework for considering and assembling the overall disaster management system entities involving many BDA and IoT entities. As shown in Figure.4 the model supports multi-sourced data that is enabled by the cutting-edge BDA and

IoT technologies and techniques. The model consists of five layers, which are briefly discussed in the subsequent sections.

A. DATA GENERATION

The data generation layer consists of all the potential data sources that are useful for developing situational awareness and providing new insights for the incident. Apart from traditional disaster management data sources (i.e., field survey, GIS-based data) a massive amount of valuable data is generated by human and physical sensing resources that can be utilized for disaster management processes to enhance operations and gain new insights. IoT-based devices provide factual data while crowd-sourced data from social media streams provides real-time information but in an unstructured format. Remote sensing data are essential in disaster management, particularly in response and monitoring phases as they provide a large area of coverage and location observation. Geo-portals contain the open-source spatial data regarding the incident area, which is useful for mapping and visualization. An important data source is the authoritative/archived data owned by the government and NGOs, which contains historical and survey data reports that intend to be embedded for effective analysis.

B. DATA HARVESTING

Data harvesting is triggered by the disaster event to engage all the dedicated and available data sources. It is important to tackle big data close to the source, especially in emergency response systems, with the intent to decrease irrelevant content, subsequently assisting real-time processing and improving access time for information [76]. The resource discovery component identifies the availability and accessibility of diverse and distributed data sources that are relevant to disaster management. Content delivery networks allocate specific tasks to a distributed system and improve response time. Load balancer is responsible to ensure maximized throughput, increased capacity and reliability of applications. Fault detection mechanism identifies hardware or software failures and saves time in troubleshooting. Data aggregators need to be utilized fittingly, as data is collected from some sources (e.g., authoritative/archived data, geo-portals) in large repositories in the form of batches, while at a rapid rate and in real time from other sources (e.g., social media streams, IoT-enabled sensors). Data dispatcher is responsible for dispatching processed information or queries from the system back to IoT devices or users on social media, for demanding more information and sending alerts or safety precautions. Furthermore, it is important to impose a security mechanism at the data harvesting layer before transferring the data by installing firewalls on the channel.

C. DATA COMMUNICATION

Data communication is the core layer and is responsible for transmission of data in all the proposed layers, using available communication technologies. Depending on the compatibility with the data source, various communication technologies with allocated gateways, categorized in different network type (i.e., LAN, WAN, PAN) can be integrated to enable smooth transmission in an efficient and secure manner. Wired local area communication networks (i.e., Ethernet), along with wireless local area networks (i.e., WiMAX (IEEE 802.16)) are used to provide short distances connections (e.g., office building, airport, and hospital). Wide area networks, such as general packet radio service (GPRS), Code-division multiple access (CDMA), long term evolution (LTE) and even public switched telephone network (PSTN) are suitable in the transmission of data over large areas. Zigbee (IEEE 802.15.4), Bluetooth (IEEE 802.15.1) and Wi-Fi (IEEE 802.11p) are effective short-range communication technologies that are compatible with high-level communication protocols. Notably, in emergencies, wireless communication especially satellite communication, Wi-Fi and WiMAX, has been the most effective means of communication [77].

D. DATA MANAGEMENT AND ANALYTICS

Data management and analytics is the core layer responsible for performing data filtration, programming and analytics operations. Initially, the filtration process starts with the collection of datasets from heterogeneous sources. Data conformation categorizes only potentially relevant datasets required for the incident to save processing time. Data quality parameters such as accuracy, consistency and reliability are checked in data cleansing. Classification of information retrieved from data (i.e., current status, casualties/injured reported, impact area maps, images or videos reported, instructions suggested) is performed. About a specific incident the required content is extracted from classification. The location co-ordinates attached to the data readings, maps and geo-tagged social media posts are extracted for mapping. This method of filtering and categorizing data will help in managing data for analysis and reduce storage space, hence decrease the computational overhead for data analytics.

A set of data programming tasks are proposed to ensure effective analysis according to the results required for disaster management. The programming tasks are based on the decision model, which is the template that defines how the essential goals are perceived, organized and processed to reach a specific decision. Technologies for multi-source information fusion combine essential information from massive heterogeneous multi-source data. Event detection in real time that is backed by social media and multiple sensor data is critical for disaster management. Semantic engine is used for effective knowledge management by searching, extracting and categorizing unstructured information. Pattern recognition provides machine learning ability to detect the configuration of features and identify the required information from textual or image/spatial datasets.

Analyses related to disasters are time-critical in nature and with huge volumes of streaming data at the back-end, demand significant computational power for accurate and high-speed processing. These constraints demand for processing the

TABLE 5. Comparison of IoT and BDA assisted disaster management use cases.

Use Cases	Benefits	Study	IoT Devices	BDA Applications	Data Type
Early Warning	Timely and exact cautionary alert acknowledgement of a disastrous event	[78]	Multiple sensors	Text mining, Semantic analytics	Textual
		[79]	Remote sensing, Observatory sensors	Data mining, Spatial data analytics	Textual, Image/video
		[80]	Smartphones	Spatial data analytics	Textual, Spatial
Evacuation	Quick and accurate identification of evacuation routes for occupants following a disaster	[81]	Vehicular sensors	Streaming analytics	Textual
		[82]	Smartphones	Location Intelligence	Spatial
		[83]	Mobile-nodes	Map-matching visual analytics	Spatial
Monitoring	Better situational awareness enabling faster and effective response/recovery operations at a lower cost	[84]	Cameras	Image-processing, Visual analytics	Image/video
		[85]	Multiple sensors	Convolutional neural network (CNN)	Textual, Image/video
		[86]	Multiple sensors	Data mining	Textual
Prediction	Forecasting potential disaster risks in advance	[87]	Multiple sensors	Machine learning	Textual
		[88]	Multiple sensors	Deep learning	Textual
		[89]	Multiple sensors	K-mean clustering	Textual

resource data through a combination of cutting-edge powerful big data analytics tools. A state-of-the-art solution for this environment would be a combination of the Hadoop Ecosystem and the Spark analytics engine. Hadoop is considered the backbone of any big data architecture. It is an open-source software platform that supports enormous data storage and processing. It is a much cheaper and effective solution than running a dedicated data center. While, Spark, an open-source in-memory data processing framework is suitable for interactive data queries and enables processing of real-time data streams with the combination of its application-specific libraries. Spark, can be used with Hadoop data source as a programming model for processing. Moreover, a combination of different machine learning algorithms, natural language processing and data mining techniques can be used for further analysis. The obvious aim of deploying state-of-the-art data analytic tools is to facilitate the decision-making process with a continuous flow of reliable and updated information extracted from multiple resources.

E. APPLICATIONS

The huge sets of valuable data resources backed by powerful data analytics, enables the application layer to implement an interface that allows interactive reporting and visualization of information to non-technical decision makers (i.e., emergency responders) in real-time. BDA application services can integrate with different disaster management expert systems designed to alert, report, monitor and detect/predict disaster situations (i.e., early warning systems and emergency response systems). The application layer should operate on a web-based access control API to prevent unauthorized access. The application interface needs to support different visual tools for generating reports in an interactive manner.

VI. USE CASES

This section presents some of the important use cases for IoT and BDA enabled disaster management with the aim to highlight the capability and importance of the said technologies. The selection of use cases considers the sequence of disaster management operations to present an overall picture of the disaster management environments where IoT and BDA play an important role. As presented in Table 5, most of the use cases are focusing on the collaborative deployment of multiple sensors (i.e., weather station sensors, cameras, GPS, wearable sensors, smartphones, etc). These different types of sensors provide huge volumes of heterogeneous data (i.e., textual, image/video and spatial) through IoT. However, with supportive BDA applications, it is possible to process the collected datasets that enables much richer and effective systems. Moreover, the mode of processing is more towards real-time applications, which makes sense due to the involvement of BDA and IoT based applications.

A. EARLY WARNING

Early warning for disasters (i.e., floods, landslides, tsunami, forest fires, storms etc.) can prevent loss of lives and minimize the disaster's impact costs. A warning notified with sufficient time before the disaster will allow people to evacuate the area and help the emergency responders to organize and take the necessary precautionary actions. Structure of the early warning system is determined by the goals it desires to achieve, considering timely and accurate information processing regarding an upcoming event. Early warning systems for environmental disaster management are mostly involving IoT [78]. Early warning systems receive the data from real-time sensors, process the information and provide an interactive warning service for more information. However, big data challenges need to be solved during the development and application of such IoT-based information systems [79]. Moreover, with the evolution and widespread use of different of IoT devices such as Smartphones, it is possible to deploy their embedded sensors (GPS, accelerometers, gyroscopes, etc.) to monitor and provide valuable data for early warning systems [80].

B. EVACUATION

The instantaneous and accurate identification of evacuation paths following a natural disaster is critical to saving the lives of the occupants. Quickly understanding the damage situations through appropriate data and processing techniques can lead to effective evacuation. In the event of a large-scale disaster, ensuring minimum road congestions are important for evacuation plans. The evacuees need to be guided towards safe and least congested routes to decrease the evacuation time. For the transportation network, real-time road situations need to be considered to compute and identify the maximum flow capacity of the roads [81]. Evacuees can also contribute for identifying blocked and congested roads using their smartphones and share the information with each other through short-range wireless communications. This approach can not only navigate the evacuees to safe places but also help in aggregating disaster-related information [82] [83].

C. MONITORING

Disaster monitoring service aims at providing effective response and recovery operations in both pre- and post-disaster situations. Due to the increasing usage of state-of-the-art technologies such as IoT and BDA, disaster monitoring service is getting faster, reliable, effective and more situational aware. Conventional disaster monitoring systems are often costly and time-consuming as they appoint only gauge sensors that could only measure one-dimensional physical parameters. However, advanced disaster monitoring systems are involving multiple data sources to geographically detect and visually monitor disaster events at a lower cost. For instance, through image-based automated monitoring, surveillance cameras are transformed into visual sensors [84]. This approach of visual sensing provides spatiotemporal information that can be utilized for a reliable automated remote monitoring of floods. With the aid of deep learning methods, multiple data sources such as map-based web services, sensors, and video cameras can be incorporated to perform real-time monitoring [85]. Moreover, disaster monitoring can benefit from the convergence of different technologies to analyze huge sets IoT extracted data with data mining techniques and identify emerging risks and changes in weather for potential disasters [86].

D. PREDICTION

Disaster occurrence is out of human control; however, through the deployment of various state-of-the-art smart technologies, we can predict, mitigate and even prevent the loss of human lives and infrastructure. Research in the field of disaster prediction has shifted from statistical and theoretical submissions to successful real-world applications. With the advancement in IoT and BDA technologies, disaster prediction systems are getting great success to minimize the adversity caused by disaster such as floods, wildfires, hurricanes, tsunamis etc. Promising innovations in technology such as IoT based IP-based sensor networks and evolving techniques of machine learning are being deployed for disaster predictions [87]. Within the scope of smart cities, disaster predictions are becoming a reality through deep learning techniques backed by IoT big data [88]. Moreover, the convergence of IoT big data and high-performance computing (HPC) can provide the capability of real-time disaster predictions [89].

VII. OPEN RESEARCH CHALLENGES

This section highlights the main open research challenges that need to be explored in the future to have better understanding and development related knowledge of the desire research area.

A. DISASTER DATA QUALITY

The quality of the collected data is very critical for disaster management, as noisy, incomplete and error-prone data can lead to serious problems and wastage of precious time in a disaster scenario. This factor is an additional overhead for BDA- and IoT-based disaster management environments, which requires to be solved prior to any kind of analysis. Data quality parameter plays a major role in determining the accuracy of the analysis carried out on a particular dataset. Table 6 describes five proposed parameters of data quality that are commonly recognized and are suitable to formulate the disaster data in the filtration process. Each dataset needs to satisfy the conditions describe against the specified parameter in order to be eligible for further processing. Many filtration algorithms and data format converters are being proposed on a regular basis; however, it remains an open research challenge for disaster management where data quality should have the highest priority.

B. WHERE IS DISASTER DATASET'S METADATA?

Metadata extraction from multiple heterogeneous data sources for a time-sensitive and data quality critical application like disaster management is an important challenge. The essential metadata information about the datasets, i.e., data source, content, time stamps, spatial reference are very important to be identified, in the context of this environment. With effective extraction of metadata, a lot of data quality concerns and integration issues can also be solved at the grassroots

TABLE 6. Disaster data quality parameters.

Parameter	Conditions
Accessibility	Is the data access public or proprietary? Whether the data has any rights or legal concentrates on usage? Whether the data needs a special aggregator to collect?
Timeliness	Whether the data is gathered on run-time or through the historical database? Does the data require to be updated in intervals?
Credibility	Is the data source identified? Can any organization or system verify the source?
Accuracy	Is the data related to the incident/crisis/disaster in any sense? Is the data free from data redundancy?
Completeness	Is the data clear and understandable? Can the data be classified to gain the desired results?

level, and reliable datasets can be provided for the disaster management operations.

C. MULTI-SOURCED DISASTER DATA AGGREGATION

Collecting disaster-related data from heterogeneous sources and integrating that voluminous data in real time is a challenging activity. Moreover, data needs to be collected from multiple geographically distrusted servers which in return make the aggregation process more difficult. Data aggregator normally handles the collection and integration of similar data to tackle the data redundancy problem and minimize resource consumption. However, the data aggregation problems raise with the increasing number of data sources, demanding more storage and computation power.

D. BUT WHICH DATA ANALYTICS APPLICATION?

Selecting the type of analysis to be performed on the newly acquired big datasets within the scope of disaster response or management can be a challenging task. The choice of a particular analysis method will determine the effectiveness and performance of the overall environment and hence will eventually affect decision making. Moreover, the desirable analysis and results may demand a combination of different analytical methods that can increase system workload and affect performance. Another challenge is to identify and analyze what data sets can support smooth and effective processing in real-time and hence provide accurate results.

E. TIME CONSTRAINT FOR QUICK RESPONSE

Due to huge data volumes, it is quite difficult to extract quality information in a limited time for effective decision-making to emergency responses. The data processing is time-consuming, as it involves multi-sourced data harvesting, filtering, and categorizing; that can take a lot of time even with advanced big data analytical tools. It is an important challenge for the existing techniques and tools to preprocess data and generate the required results in a specified amount of time to provide quick emergency response and save lives.

F. ARCHITECTURAL CHALLENGES

Due to the lack of a defined model for BDA- and IoT-based disaster management environment in the existing literature, detailed observations of different related reference models is required. The architecture for such an environment needs to be flexible to accommodate all the data sources, consistent to configure different network topologies for data communication and supportive to fetch the required results for effective decision-making. Moreover, the architecture should be designed to keep the environment resilient so it can handle any type of disruption caused by disasters. With multi-sourced data, it is challenging to design a generic data model that integrates heterogeneous data while being flexible, effective and secure.

G. FAULT TOLERANCE DURING DISASTERS

Fault tolerance is the ability of the system to work effectively even in the case of a hardware or software failure. With heterogeneous and distributed data source environments there is always a chance for some hardware devices and sensors to fail because of physical damage or disruption in communication channels, particularly in a disastrous situation. The BDA- and IoT-based environment having distributed components, predominantly its data sources can be affected by the disaster as well. Hence, disaster resilient system architecture needs to be planned, so that the data can be effectively channelized and processed even in the course of any destruction. Data sources are critical in the successful deployment of the environment and should be able to generate data with infrastructure impairment and power blackouts. Hence backup power consumption mechanism and data management capabilities; such as a redundant backup system or cloud-based distributed storage system with distributed computing facilities needs to be established.

H. PRIVACY AND SECURITY

Privacy concerns have been a serious issue in both big data and IoT domains, as open personal information is widely utilized which, if misused can lead to threats such as profiling, tracking, theft, and discrimination [90]. Big data usually contains some sort of confidential information related to people or government and hence high-level security is required as the data moves over different types of networks. Social media data sources can increase privacy concerns as its data sets contain personal details and location of the users. These data sets can be very sensitive in crisis like civil wars and resistance movements. Additionally, open source big data analytics tools and most of the technologies in the Hadoop Ecosystem lack sufficient security mechanism [91]. Managing the access control of the big disaster datasets is vital to safeguard against any malicious use of data, hence proper security mechanism is required to ensure data protection.

I. STANDARDIZATION CHALLENGE

Standardization of IoT in general and big data, in particular, is still in its infancy. Standards can promote system efficiency, foster technological changes and provide recognized guidelines for policy, governance and future research. As disaster management requires various systematic solutions, it can be difficult to develop standards initially. However, standards such as communication protocols, security protocols, metadata and data aggregation standards are the core activities that need to be formalized to increase the value of disaster management environments and services.

VIII. CONCLUSION

The fusion of BDA and IoT promises a new and more effective approach for carrying out the core operations of disaster management processes. With state-of-the-art big data analytical tools and well-managed IoT, we can not only harvest large volumes of valuable data from multiple data sources but can also generate required results in real time for an effective decision-making. However, a lot of research is still required to productively model and implement these two paradigms, keeping in view the time constraint and accuracy demands of disaster management processes. In this survey paper, we identified the benefits of BDA- and IoT-based disaster management and investigated the state-of-the-art literature conducted regarding BDA and IoT applications for disaster management. We classified the related literature by presenting a thematic taxonomy that unearths the main attributes of BDA- and IoT-based disaster management environments. We also presented a thorough overview of the overall architectural deployment of BDA- and IoT-based disaster management environments through a reference model having dedicated layers, such as data generation, harvesting, communication, management and analytics, and applications. We discussed and compared some indispensable use cases to show the role of BDA and IoT in different disaster management phases. Moreover, we sketched out the key requirements for the successful deployment of the environment and the challenges that need to be resolved. We conclude that this survey can be used as a guideline to understand the overall functionalities for productive utilization of the opportunities associated with BDA and IoT towards the construction of an effective disaster management environment.

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