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Digital transformation in disaster management: A literature review

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ABSTRACT

While there have been studies focused on digital transformation (DT) in industry, we lack an understanding of how it materializes in disaster management (DM). This research provides a literature review of IT-enabled and digital initiatives in DM and examines the potential for DT in the field. We analyzed 254 articles from six different disciplines on the use of digital technology in DM and then developed a framework that organizes the central concept of DT in DM around five key areas. Using this framework, we explain the key digital capabilities necessary in DM to develop and implement authority- or public-driven initiatives, articulate and demonstrate DT differences in the industry setting, and provide avenues for future research in this area.

Introduction

The application of digital technologies has become critical to disaster management (DM). Events such as the Covid-19 pandemic illustrate the potential of digital technologies to support DM, such as through contact tracing apps (Trang et al., 2020), smart management systems to analyze movements of infected people in real-time (Comfort et al., 2020), and machine learning (ML)-based tools based on social media data to predict the number of Covid-19 infections (Budd et al., 2020). More broadly, digital technologies support DM functions such as early warning (Chatfield et al., 2013), risk analysis (Pence et al., 2019), situational awareness (Luokkala & Virrantaus, 2014), and command and control (Bunker et al., 2015) in disasters such as flooding (Tim et al., 2017), and terrorist attacks (Oh et al., 2013).

Initial research focused on tools such as professional response software, databases, and radio equipment (e.g., Allen et al., 2014; Chen et al., 2008; Turoff et al., 2004); scholarly interest has broadened more recently to encompass what scholars refer to as “digital technologies,” such as social media (Ling et al., 2015; Tim et al., 2017), mobile (Baytiyeh, 2018; Tan et al., 2017), analytics (Brem et al., 2021; Liao et al., 2012), cloud (Ujjwal et al., 2019; Wilkinson et al., 2015), DM platforms (Li et al., 2013; Poblet et al., 2018), and the Internet of Things (IoT) (Khan et al., 2020; Lauras et al., 2015).

The use of digital technology is often considered a catalyst of digital transformation (DT)—although the mere fact that an organization uses digital technology does not imply the organization undergoes an actual DT. Scholars have noted that the quest for opportunities offered by digital technology often leads to redesigning business processes, reshaping organizational structures, and unlocking new value-generating possibilities that can lead to DT (Vial, 2019).

However, this scholarship on what DT is, why it may be beneficial, and how to orchestrate it successfully, has been largely

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developed in the corporate context. Despite any intuitive notion that digital technologies can aid DM, there is limited understanding of whether they have transformed DM—a domain that presents unique challenges. It requires intricate coordination and information exchange among various responder organizations and the public (Bunker et al., 2015). There is often a need to establish provisional organizational structures under time pressure (Tim et al., 2017). DM also operates amidst several uncertainties: resources must be supplied and managed by multiple stakeholders with different objectives (Bunker et al., 2015); it requires planning for failure of the critical infrastructure (Kulawiak & Lubniewski, 2014); and prompt decisions based on limited information are necessary (Peng et al., 2011).

The goal of our review is to survey current literature and identify digitalization opportunities for DM. Previous literature reviews in this field have focused on specific technology applications such as social media and operational systems (Eismann et al., 2021; Reuter et al., 2018; Simon et al., 2015), without fully exploring the range of digital technologies to identify research gaps and opportunities for DT in DM. We aim to answer our research question:

How is the use of technology in disaster management advancing to create patterns of, or leading to, digital transformation?

To answer this research question, we conducted a theoretical literature review (Paré et al., 2015) to connect research in DT, most of which is in a corporate context, with DM. To analyze the DM literature from the DT perspective, we draw on the distinction between digital initiatives (Piccoli et al., 2022), which we conceive as a driver of DT, and IT-centric initiatives as drivers of IT-enabled organizational change (Wessel et al., 2021). Hence, DT consists in restructuring the value creation and organizational processes around the generation and integration of digital resources. A digital initiative aims to harness these digital resources for value creation (Piccoli et al., 2022). This delineation is crucial for recognizing and leveraging emergent DT opportunities in DM.

Our work makes two major contributions. The first is the framework we developed, derived from relevant literature on the intersection of DM and DT, which clarifies fundamental capabilities and their interrelationships that can lead to IT-enabled and digital initiatives within the context of DM. With this framework, we organize the currently fragmented state of research on DT in DM and develop a common set of concepts and vocabulary for future research across disciplines. The second is that we contrast DT in DM to DT in industry, identifying and outlining critical avenues for future research of DT in DM. Recognizing the rapidly evolving nature of both IT-enabled and digital initiatives in DM, we pinpoint pressing questions and unexplored areas that warrant further investigation.

Investigative context

In the following sections, we first define disaster and DM, then digital initiatives, and explain how digital initiatives can lead to DT. We also discuss the difference between IT-enabled and digital transformation and explain what we mean by a digital ecosystem.

Disaster and disaster management

Disasters are “serious disruptions to the functioning of a community that exceed its capacity to cope using its own resources” (IFRC, 2013). What all disasters have in common is large-scale and widespread disruption of the routine functioning of government, business, society, and affected communities, such as limiting access to physical and social infrastructure, housing destruction, dislocation of populations, business interruptions, and physical harm (Sakurai & Kokuryo, 2014). They differ by cause (e.g., geophysical, meteorological), severity, urgency (e.g., they may evolve quickly or slowly), and they can trigger one another in a cascade, such as a tsunami reputedly causing the Fukushima 2011 nuclear power plant disaster. Disasters are complex because they can potentially cascade and compound their impacts on people and assets, and because the degree to which these are susceptible to the disaster’s impact are uncertain (Pescaroli et al., 2018).

Disaster management is the effective orchestration of the ensemble of actions taken by public and private responder organizations (e.g., government agencies, firefighters, paramedics, police) to mitigate, prepare, respond, and recover from disasters. These functions also define the phases of DM. Mitigation and preparedness typically precede a disaster (pre-disaster management), while response and recovery follow it (post-disaster management) (Khan et al., 2020). The use and processing of digital data can significantly support the tasks in these phases. In pre-disaster *mitigation*, for example, where the aim is to reduce or eliminate the potential effect of a disaster by taking preventive and protective actions, using environmental data to run flood simulations—to assess water level and flow—can support the decisions to build dams around a river to prevent flooding.

Disaster *preparedness* is crucial for disasters that cannot be prevented. Preparedness measures focus on assessing and planning aid delivery to affected communities, and increasing communities’ resilience. Satellite weather data, for example, are critical to early hurricane warnings by enabling forecasting of tropical storms trajectories.

The *response* phase entails activities to cope with a disaster’s impacts. With respect to data, the focus is on collecting and processing real-time data from sensing technologies to inform actions to cope with a disaster, such as data for guiding search and rescue operations.

Finally, *recovery* focuses on long-term stabilization, with the aim of rebuilding a community affected by a disaster (Altay & Green, 2006). Data in this phase may be collected for damage assessments of buildings and to organize financial support of victims (Fujita & Hatayama, 2021).

Digital initiative

In the DM context, a *digital initiative* is the ensemble of actions aiming at improving the execution of one or more DM tasks by leveraging digital resources. The theoretical distinction between digital initiatives and other sorts of technology-dependent initiatives is critical to comprehending, identifying, and capitalizing on nascent opportunities for DT in DM. Digital initiatives do not necessarily lead to DT; such transformation implies a radical reorganization of value creation and organizational processes around the creation and recombination of digital resources, and can be carried out without substantially altering an organization's structure (Piccoli et al., 2022).

Digital resources, consisting of both digital assets and digital capabilities, are a class of IT resources that are: 1) *modular*, that is, structurally independent yet recombinable within a system architecture; 2) *encapsulate objects of value,* that is, have the potential to generate value; and 3) *accessible by means of a programmatic interface,* that is, are accessible programmatically, typically through APIs (Piccoli et al., 2022).

Digital elevation models[1] are an example of representations of the topographic surface transformed in a digital asset: they are *modular* because they are raster GIS layers and can work as units of larger systems, such as hydrological models; encapsulate objects of value, as in when they are used by insurance companies to assess risk exposure and calculate insurance premiums; and are *accessible programmatically* through ArcGIS Hub API.

Digital capabilities are "repeatable patterns of organizational actions yielding capacity to undertake activities that a firm can access programmatically through a programmatic digital interface" (Piccoli et al., 2022, p. 2295). Not all technology-enabled capabilities, though, are "digital." For example, a responder organization's ability to monitor social media for coordinating search-and-rescue operations should be considered an IT capability, but it can morph into a digital capability if the organization modularizes and makes it available programmatically for the benefit of other responder organizations or rescue teams.

A digital initiative involving climate record data, undertaken by the U.S. government's National Oceanographic and Atmospheric Administration (NOAA), provides a good example of how an initiative involves digital assets and capabilities. Traditionally, NOAA has collected these data in a repository, which—while constituting an object of value—is a mere IT asset unless it is modularized and made accessible through a programmatic interface. NOAA morphed a multitude of its data repositories into digital assets by creating OneStop, a platform to access data such as climate records through an API,[2] thereby meeting the three criteria to consider a resource "digital." Similarly, simulation-based weather forecasting, an IT capability, became a digital capability because it is exposed through API access, allowing it to fetch data on active tropical storms and integrate that capability with other capabilities, such as business continuity planning in supply chain operations.

From digital initiatives to digital transformation

Scholars largely agree that DT implies organizational transformation. Unlike IT-enabled transformation, which primarily supports an organization's existing value proposition and reinforces its identity, DT (re)defines the value proposition and organizational identity (Wessel et al., 2021), such as by transforming the organization into a digital-first one (Baskerville et al., 2020). Presumably, such transformation occurs through the effective orchestration of digital initiatives, which redesign value creation and organizational processes to revolve around digital resources (Piccoli et al., 2022).

Table 1 shows the key dimensions and differences between IT-enabled and digital transformation.

Digital ecosystems

A digital ecosystem is the network of interconnected digital platforms, services, and technologies that work together to enable DT. Research in the industry context has argued that digital initiatives thrive in ecosystems that are *infrastructural, combinatorial,* and *servitized* (Piccoli et al., 2022); presumably, so does DT. A *combinatorial* ecosystem is one in which resources can be restructured together to be accessed through interfaces. An interface provides users with an adequate gradient of abstraction to access the output of a recombination of technological components. The role of an interface is to encapsulate the underlying technologies into a coherent module. Examples include Corona dashboards to visualize Covid-related data (Recker, 2021) and NOAA's API enabling access to the OneStop repository of climate data.

Servitization refers to an ecosystem in which value creation mechanisms (e.g., contractual elements) can be fully programmed into digital resources. The German Modular Warning System (MoWaS), a digital web-based platform to dispatch warnings via different channels (e.g., warning apps), is an example. While most warnings must be approved by the responsible authority, the German weather service and flooding centers have direct access to MoWaS for dispatching severe weather and flooding alerts.[3]

Infrastructural refers to the "widespread availability of shared, unbounded, heterogeneous, open, and evolving digital information infrastructures on which to envision and deploy value creating digital strategic initiatives" (Piccoli et al., 2022, p. 2297). Protocols, networking hardware, and so on are all elements that constitute the internet infrastructure. Literature in DT generally assumes infrastructural elements are reliably available to enable digital initiatives. What is peculiar about the DM context, however, is that disasters themselves could disrupt infrastructural elements (e.g., networking hardware) on which digital initiatives rely. Although even major infrastructure failures can be addressed—for example, using Space X's Starlink to compensate for lack of internet connectivity—vulnerability or instability of infrastructural ecosystem are critical stressors for the successful implementation of technology-related initiatives in DM.

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[1] https://www.usgs.gov/faqs/what-digital-elevation-model-dem (accessed May 8, 2024).

[2] https://data.noaa.gov/onestop/ (accessed May 8, 2024).

[3] https://warnung.bund.de/ (accessed May 8, 2024).

Table 1
Characteristics of IT-enabled vis-a-vis Digital Transformations.

Dimension		IT	Digital
Resources	Assets	Hardware, software, data, and programs within the organization's control and boundaries (Piccoli et al. 2022).	IT assets that are "modularized and exposed through a programmatic interface that embeds technical and governance specifications for their use" (Piccoli et al. 2022, p. 2295).
	Capabilities	Human and organizational competencies related to IT, such as IS-business partnerships and software development skills.	"Repeatable patterns of organizational actions yielding capacity to undertake activities that a firm can access programmatically through a programmatic digital interface" (Piccoli et al. 2022, p. 2295).
Initiative		Ensemble of actions aimed at improving the execution of one or more DM tasks by leveraging IT resources.	Ensemble of actions aimed at improving the execution of one or more DM tasks by leveraging digital resources and a necessary (but not sufficient) condition to enable DT.
Transformation		The use of technology supports the current value proposition and reinforces the organizational identity (Wessel et al., 2021).	The use of digital resources to redefine the value proposition into a digital-first organization (Piccoli et al., 2022), accompanied by the emergence of a new organizational identity (Wessel et al., 2021).

Method

We conducted a *theoretical review* to identify DT initiatives in DM. The goal of a theoretical review is to explain and establish concepts and their relationships that contribute to dimensions of a conceptual framework (Rowe, 2014). We aimed to synthesize the insights of conceptual and empirical studies from different DM research strands that, in turn, provide the input for identifying, describing, and integrating concepts from the literature on DT based on our conceptual framework (see theoretical background section) (Paré et al., 2015). The review process consisted of *defining* the scope of the literature search, *search* and *selection* of relevant papers, *forward and backward search* based on the initially selected papers, and *qualitative analysis* of the final literature corpus (Paré et al., 2016). Each step is detailed below.

In the first step, we *defined* the scope of our review, that is, our inclusion and exclusion criteria. Given that the concept of DT has been rarely or only loosely applied in the DM literature, we began our search by identifying articles that studied the use of technologies such as social media, mobile, analytics, IoT, or digital platforms, since they have been associated with DT (Vial, 2019). This resulted in a very large number of articles, leading us to scope relevant research fields using the Journal Quality List (JQL) *meta*-ranking (Harzing, 2019) to identify relevant subject areas and associated journals. We ensured that the journals we retrieved are ranked high in most of the JQL's rankings (Harzing, 2019) and A* in the ABCD list (Australian Business Deans Council, 2019), and that they are relevant to the topic. This resulted in a sample of 35 journals. We also added three journals that published articles covering DM topics but did not meet the quality criteria: 1) *Information System Frontiers*, which has published several special issues on DM; 2) *Government Information Quarterly*, which has published research on public authority use of DM-related technologies; and 3) *Technological Forecasting and Social Change*, which has published on technological DM trends. We then selected journals in *disaster management*. While relevant to the DM community, these journals often did not appear on the JQL. Furthermore, because they are not business journals, only a few were on the ABCD list. We selected six of these disaster management journals based on an impact factor of 4 or higher. In total, we selected 42 journals from six subject areas. Table 2 shows the final list of subject areas and journals.

In the second step, we used Web of Science to *search* for articles in our sample of 42 journals using our defined search terms—"digital, technology, information system" and "disaster, crisis, emergency, hazard"—in either the title, abstract, or keywords. No time constrain was imposed. This yielded 1,043 articles.

In the third step, we *selected* relevant papers from the 1,043 articles identified in the preceding step. For an article to be included in the relevant sample, it had to focus on technology use and development in DM. We excluded duplicates and calls for papers, as well as papers unrelated to our topics, such as those in which the terms "crisis" or "disaster" did not align with our definition (e.g., financial crisis, cybersecurity, or healthcare emergency operations). By screening titles and abstracts, and content, when necessary, we excluded 909 articles. Finally, in a *forward and backward search*, we added 120 articles, resulting in a final sample of 254 articles. Table 2 shows the journals selected and the inclusion/exclusion of articles in the different steps.

In the last step, we began with *first-order analysis* as indicated by Gioia et al. (2013), which consists of extracting first-order concepts followed by abstraction to second-order and, finally, an aggregated dimension representing theory-centric themes. In particular, we began to pre-structure our data searching for first-order concepts, considering our theoretical framework of IT-enabled and digital initiatives. We identified statements for coding, ranging from phrases to sentences to paragraphs, in five major areas. First, we looked for concepts in which the papers referred to *capabilities needed* to implement digital technologies, extracting first-order concepts related to data generation and processing, that is, sensing, storage, sharing, dissemination and alerting, analyzing, and visualization. In this coding, we also identified capabilities that support the initiation of digital initiatives, extracting first-order concepts related to concepts that facilitate the implementation of initiatives. We deemed these concepts relevant to understanding requirements for developing and/or using digital technologies in DM and how they might differ from those in the DT literature. Second, we coded the types of *organizations involved* in an initiative, extracting first-order concepts based on organizations or stakeholders mentioned. We deemed these concepts relevant to understanding the extent to which the organizations studied for DM mirror types of organizations studied in the DT literature. Third, we coded the *challenges* organizations face when carrying out initiatives, extracting first-order concepts based on risks and challenges of a DM initiative. We also looked for instances of *value*, often implicit, that an initiative brings to DM; here we

Table 2
Overview of Selected Articles by Subject Areas.

Subject area (Harzing List)	Selected journals	Initial search	Excluded through screening	Forward & backward search	Final sample
Management Information Systems, Knowledge Management	11	122	91	30	61
Journals: MIS Quarterly, Decision Support Systems, European Journal of Information Systems, Information and Management, Information Systems Journal, Information Systems Research, Journal of Information Technology, Journal of Management Information Systems, Journal of Strategic Information Systems, Journal of the Association for Information Science and Technology, Information Systems Frontiers					
Public Sector Management	7	37	29	7	15
Journals: Environment and Planning A, Environment and Planning B: Planning and Design, Gender and Society, Public Administration Review, Regional Studies, Urban Studies, Government Information Quarterly					
Innovation	3	79	71	12	20
Journals: Technological Forecasting and Social Change, Journal of Product Innovation Management, Transportation Research, Part C: Emerging Technologies					
General & Strategy	8	13	13	0	0
Journals: Journal of Management Studies, Academy of Management, Annals Academy of Management Journal, Academy of Management Review, Administrative Science Quarterly, Journal of Management, Organizational Research Methods, Strategic Management Journal					
Organizational Strategy/Organizational Behavior	7	12	8	0	4
Journals: Industrial Relations, Journal of Conflict Resolution, Journal of Organizational Behavior, Journal of Vocational Behavior, Leadership Quarterly, Organization Science, Organization Studies					
Disaster Management	6	780	697	71	154
Journals: International Journal of Disaster Risk Reduction, Safety Science, Journal of Climate, Journal of Environmental Management, Risk Analysis, Nature Climate Change					
Total	42	1043	909	120	254

also coded the DM functions an initiative supported. Finally, the first and second author classified technology-dependent initiatives, whenever possible, as either digital or IT-enabled.

The first and second authors discussed new insights in regular meetings and adapted the coding accordingly. Upon agreement of the set of first-order concepts, the two authors discussed how these first-order concepts fit into second-order themes and then into aggregated dimensions. Once a clear set of dimensions and themes had been created, we performed selective coding aimed at uncovering the interrelations between the categories and relating them to each other (see Fig. 1).

Results

In this section, we discuss research showing how technology can support different DM capabilities. We also discuss how technological innovation may lead to DT, as Fig. 1 summarizes. In particular, we postulate that data-related capabilities (i.e., *data sensing* and *data processing*) are at the core of technology-related—that is, IT-enabled and digital—initiatives in DM. We introduce *supporting IT and digital capabilities*—crowdsourcing, IT-enabled training, and IT project management skills—which provide resources (e.g., data, digital workforce) and skills (e.g., knowledge about coding) that facilitate the development and implementation of initiatives. We elaborate on the types of organizations that lead such initiatives, including public authorities and the public itself (e.g., volunteer organizations, self-organized groups, local communities). Authority-driven responses are top-down initiatives directed by public authorities,

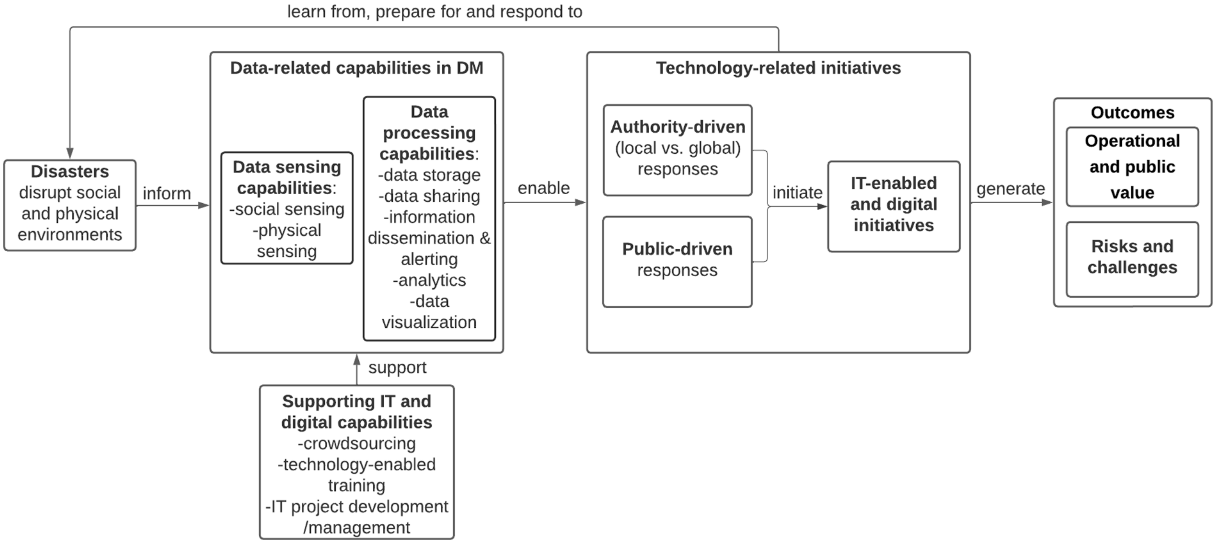

Fig. 1. IT-enabled and Digital Initiatives in DM.

governing bodies, and so on; public-driven initiatives arise from the public, leveraging bottom-up efforts and community collaboration. Finally, we elaborate on the value such initiatives provide, which is both "operational" and "public," as well as the risks and challenges initiatives present.

Leveraging digital technology for data collection in disaster management

Researchers have studied how digital technologies help in coping with a variety of disasters, with a focus on natural disasters, such as tsunamis (Ai et al., 2016), tornados (Schumann et al., 2018), flooding (Ling et al., 2015), earthquakes (Fujita & Hatayama, 2021), and volcanic eruptions (Inan et al., 2018). We also found studies on using technology to help cope with human-made disasters, such as active shooter events (Oh et al., 2013), chemical spills (Chen et al., 2008), terrorist attacks (Baytiyeh, 2018), and, more recently, public health disasters, such as the Covid-19 pandemic (Rowe et al., 2020).

Heterogeneity among types of disasters leads to major differences in the sources and types of data for describing the scope, severity, type of disaster, and so on, as well as how to leverage those data to support DM. For instance, physical remote sensors are often at the core of initiatives related to natural disasters relying on environmental data such as seismic data for earthquake detection, and rainfall and river stage data for flooding. These are the sorts of data sources that typically enable tools for earthquake damage assessment (Fujita & Hatayama, 2021) and tsunami early warning (Ai et al., 2016). Human-made disasters and health crises, in contrast, may rely more extensively on human-generated data such as interactions on social media. Notable examples include the case of a crowdsourcing tool for tracking episodes of violence during a social crisis (Poblet et al., 2018) and contact tracing apps for tracing infection chains during Covid-19 (Rowe et al., 2020).

Data-related disaster management capabilities

Data-related DM capabilities refer to the ability to sense and process disaster-related data in ways that support digital and IT-enabled initiatives. Table 3 lists such capabilities and examples of how they can be deployed to support IT-enabled or digital initiatives.

Data sensing capabilities

The capacity to collect accurate and up-to-date data on disasters is a fundamental aspect of disaster management for many purposes, including the measurement of attributes of a disaster, such as type, location, and severity; and the assessment of a disaster's potential or actual impact on the community, critical infrastructure, and buildings. Other purposes include: to identify evacuation routes; assess shortages in resources such as water, power, and gas; and identify constraints in the provision of public services such as hospitals (Kankanamge et al., 2019; Mejri et al., 2017).

Historically, DM has relied on physical and human sensors. Thus, it comes as no surprise with the evolution of technology, physical sensing (e.g., river gauges, satellite imagery, weather stations) has provided more and higher-quality data. But in addition to that, inexpensive, ubiquitous digital technologies have enhanced opportunities for social sensing, that is, collecting data through human presence. Sensors such as GPS trackers, accelerometers, and gyroscopes are built into mobile devices and wearables, allowing the collection of disaster-related data through users' presence even without their active participation.

Physical sensing capabilities

Physical sensors, which are devices deployed to sense physical properties of the environment (e.g., temperature, pressure, water flow), are necessary assets for physical sensing capabilities. Typically, physical sensors are *dedicated* sensors, because they are designed and installed to collect data about certain events. Erd et al. (2016), for instance, present a Wireless Sensor Network (WSN) that supports firefighters in detecting infrastructure damage. The network attached to a building consists of energy-efficient wireless sensor nodes with an integrated ultrasonic sensor for collision-free data transmission to a central unit. The status of the sensors helps monitor the collapsing of the building or its parts. Other examples include river gauges to monitor rivers for flood levels (Azam et al., 2017); satellites imagery to assess environmental conditions (Kaku & Held, 2013; Zheng et al., 2021); and using processed data collected via the IoT for emergency decision making (Li et al., 2013). Physical sensors can also be *adapted* to serve some sensing capability for which they were not originally designed. For example, weather stations that collect meteorological data can be used to detect bushfires based on measures of pollutants in the air, such as carbon dioxide (Zheng et al., 2021).

We also include unmanned aerial and ground vehicles (UAV) in the category of physical sensors. Footage they collect help generate detailed, up-to-date maps of affected regions that are useful in coordinating rescue operations (Diakakis et al., 2019; Wankmüller et al., 2021), and aerial photography images from drones can be used to assess damage to buildings (Fujita & Hatayama, 2021). UAVs can complement remote sensors, providing a flexible and cost-effective solution to overcome reliability or precision issues with remote sensors (Khan et al., 2020).

Social sensing capabilities

Humans—as users of digital technologies—are increasingly leveraged as a widely deployed network of sensors. Social sensing refers to sensing opportunities created by ubiquitous human connectivity and sensorization of their mobile and wearable devices with built-in cameras, accelerometers, GPS, oscillometers, gyroscopes, barometers, and so on. *Social sensing* capabilities involve humans as "participatory" or "opportunistic" sensors (Yang et al., 2012, p. 773) and, as with physical sensors, can transpire through dedicated or adapted channels. *Participatory* social sensing requires that people interact with their devices to share information via *dedicated* DM

Table 3
Typology of Data-related DM Capabilities.

Capability	Sub-capability/Task	Examples of IT-enabled configuration	Examples of digital configuration
Sensing: The ability to collect accurate and current disaster-related information.	*Social sensing:* The ability to collect spatio-temporal disaster data from mobile phone/social media users through human presence.	Tallahassee Utilities used 311 critical service restoration requests—submitted through the DigiTally app—to inform customers about power restoration after Hurricane Michael in 2018. The requests were plotted on a power outage map. Outstanding requests were addressed following an efficiency rule to repair first whatever would restore power to the largest number of people (Xu & Tang, 2020). During the Covid-19 pandemic, countries developed and introduced smartphone apps for contact tracing based on low-power Bluetooth technology to digitally trace infections (Budd et al., 2020). In most cases, as with the Italian app *Immuni*, users were notified about a possible contact but still needed to personally notify their family doctors. At a time when shortages of Covid tests required that they be used sparingly, the app made rapid testing accessible—and then advised quarantine while waiting for instructions on what to do next.[b]	There is no evidence that DigiTally provides programmatic access to data about service requests it collects so those data can, for instance, be accessed and handled within an Outage Management System. Companies such as PowerOutageUS[a] instead offer API access to power outage data they collect to support outage management. A system-level approach is needed to integrate contact tracing and symptom tracking, with access to care and long-term follow-up and monitoring, such as through rapid testing and case isolation (Budd et al., 2020, p. 1188). COVID-19 Smart Management System, which analyzes data from public and private organizations (e.g., credit card and smartphone companies), enables automatic analysis of infected people's movements within 10 min and sharing that information with the public through cellphone text messages (Comfort et al., 2020)—although it still employs manual analysis and confirmation by humans.[c]
	Physical sensing: The ability to collect disaster-related data from physical remote sensors such as satellites, river gauges, and UAVs.	Aerial observations help determine where to intensify ground observations before critical evidence disappears, but do not replace ground observations as their accuracy is unmatched by UAV observations (Diakakis et al., 2019). Post-flood disaster investigation combining traditional on-ground post-flood observation techniques and UAV imagery to estimate discharge (Diakakis et al., 2019).	Sentinel Asia is an initiative established in 2005 as a collaboration between disaster management and regional space agencies. The initiative uses satellite imagery for an early warning system by collecting and processing raw satellite imagery data into value-added products that can be accessed by disaster management agencies through a Web-GIS (Kaku & Held, 2013).
Data processing: The ability to transfer and leverage digital information within the DM network.	*Data storage:* The ability to implement appropriate infrastructures to store disaster data.	At the U.S. National Hurricane Center, the IBTrACS project developed HURDAT, a hurricane database that provides global tropical cyclone and hurricane data (Knapp et al., 2010; Knapp et al., 2018). Currently, such data are not exposed programmatically, although Python interfaces have been built (e.g., https://github.com/miniufo/besttracks).	Cloud-based data storage (e.g., Azure Cloud Platform, AmazonEC2) that provide scalable computation, storage, and networking, and enable migrating DM models and technologies into the cloud for better flexibility, scalability, access, and performance (Ujjwal et al., 2019). To create a Covid-19 dashboard, data were sourced from hundreds of local health administration offices, sometimes requiring substantial manual effort. They were then made available through the common data infrastructure (Recker, 2021).
	Data sharing: The ability to implement appropriate infrastructures to share disaster data within the responder network.	An ecosystem in which responder organizations use their own IT systems within their organizational boundaries and control and rely on a data model that supports information exchange between different organizational systems (Chen et al., 2008).	PowerOutageUS
	Information dissemination & alerting: The ability to distribute disaster-related information to the relevant public.	A built-for-disaster purpose app to disseminate disaster information from authorities to the public; the American Red Cross Apps and the Federal Emergency Management Agency (FEMA) App are examples (Tan et al., 2017).	MoWaS, the German national warning system, is a platform that enables dispatching warnings via different channels (e.g., warning apps, sirens, TV, radio etc.) to an affected population by the authority in charge. The platform is modular: it enables adding channels (e.g., new warning apps) to the system via a programmable interface.[d]

(*continued on next page*)

Table 3 (*continued*)

Capability	Sub-capability/Task	Examples of IT-enabled configuration	Examples of digital configuration
	Data analysis: The ability to process sensed data to mitigate, prepare for, respond to, and recover from a disaster.	A case-based earthquake damage assessment of buildings based on deep learning/image recognition that learns via images that are manually labeled by volunteers or authorities (Fujita & Hatayama, 2021).	Sentinel Asia, which exposes satellite imagery through Web-GIS platform, includes a data analysis node to provide agencies with more actionable data products (Kaku & Held, 2013).
	Data visualization: The ability to visualize data in an understandable format. Unlike simple data analysis, the output of data visualization is not another data product but, rather, an information product that is readily usable for decision making.	STEPS (Simulation of Transient Evacuation and Pedestrian Movements) allows for assessing evacuation plans. It has been shown to have more persuasive power for eliciting policy changes (e.g., revising construction codes), as "the visual power of simulations (Tufte 1990) has helped engage regulators with new practices, overcoming their preference for precedent and repetition in design" (Dodgson et al., 2007, p. 860).	N/A

[a] https://poweroutage.us/ (accessed May 8, 2024).

[b] https://www.corriere.it/tecnologia/20_ottobre_08/immuni-cosa-succede-davvero-se-arriva-notifica-tutti-altri-dubbi-sull-app-e4bc13fa-08a6-11eb-ab0e-c425b38361b4.shtml (accessed May 8, 2024).

[c] https://events.development.asia/system/files/materials/2020/04/202004-covid-19-smart-management-system-sms-republic-korea.pdf (accessed May 8, 2024).

[d] https://www.bbk.bund.de/DE/Warnung-Vorsorge/Warnung-in-Deutschland/MoWaS/mowas_node.html (accessed May 8, 2024).

channels—apps and platforms designed for disaster communication and management purposes such as disaster apps (Berawi et al., 2021; Tan et al., 2017) and crowdsourcing tools (e.g., Ushahidi). Other channels not designed primarily for these purposes, such as social media, can be *adapted* to support sensing capabilities. Sharing disaster-related content via social media is an example of participatory real-time social sensing that enables public authorities to collect disaster-related data from those platforms to support situational awareness and sense-making (Mirbabaie et al., 2020).

Opportunistic social sensing refers to collecting data through built-in sensors in devices that humans typically carry, but without users' active involvement. It is "opportunistic" because it relies on sensors that are built into mobile technology and may be working in the background. Google's Android Earthquake[4] is an example of opportunistic sensing of p-waves: it integrates a network of physical sensors with accelerometers in more than 2 billion Android smartphones, transforming them into mini-seismometers.

Opportunistic social sensing may be *dedicated* or *adapted*. Covid-19 contact-tracing apps are an example of dedicated opportunistic sensing: tracking exposure to would-be positive cases required users to install and run a dedicated app that relies on Bluetooth technology and makes it possible for authorities to monitor infection chains (Budd et al., 2020).

The Smart Management System developed by the South Korean government, a comparable way to track the spread of Covid-19, uses *adapted* opportunistic sensing. Using human mobility data from public and private organizations (e.g., network providers), the system was able to analyze the movement of infected people within 10 min and share that information with the public by dispatching warnings on mobile devices (Comfort et al., 2020). The use of socially sensed data to estimate mobility of the population during Covid-19 lockdowns demonstrates how digital resources, such as data repositories, can be reconfigured quickly to evaluate the effectiveness of public health interventions by policymakers (Budd et al., 2020).

Table 4 is an overview of sensing opportunities found in the literature, along with examples.

To assess whether a social media-enabled initiative is a digital one, as opposed to merely IT-enabled, it is useful to compare social media sensing to other technology-enabled channels for social sensing. The use of social media (a so-called "digital technology") does not necessarily generate a digital resource for DM. In fact, while X (formerly Twitter) allows programmatic access to its tweets, they may not be readily usable as an emergency-related digital assets (e.g., data) for coordinating rescue or relief operations. Tweets are rarely geotagged, and thus geolocation precision is inadequate. Thus, while tweets can be accessed programmatically, the parameters necessary to provide a minimum level of functionality—to triage emergency calls, for instance—cannot, possibly requiring further manual steps.

Data processing capabilities

Streams of data from social and physical sensors require robust data processing capabilities to store, analyze, and interpret DM data efficiently. As explained in more detail in the subsequent sections, our review identified the following capabilities related to data processing: data storage, data sharing, information dissemination and alerting, analytical, and data visualization.

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[4] https://crisisresponse.google/android-alerts/ (accessed May 8, 2024).

Table 4
Types of Data Sensing.

Main data source	Type	Adapted channel	Dedicated channel
Social sensing	Participatory	Disaster-related social media communication, e.g., during an earthquake (Kankanamge et al., 2019).	A smartphone app to call disaster responders for help, e.g., SafeMyLife (Berawi et al., 2021).
	Opportunistic	Collection of mobile phone users' data. For instance, to track movements of infected people during Covid-19 (Comfort et al., 2020).	DM smartphone apps that run in the background and collect data, e.g., contact tracing apps (Budd et al., 2020).
Physical sensing		Weather stations that collect meteorological data (Zheng et al., 2021) adapted to fire detection.	Digital river gauges that measure flood levels (Azam et al., 2017).

Data storage capabilities

Data storage capabilities are the ability to implement appropriate infrastructure to store disaster data. This section reviews examples of approaches to data storage to support DM, notably through the use of databases, cloud-based architectures, and open data initiatives that make DM databases publicly accessible.

With respect to data storage assets, spatial databases have been used for data structures that represent objects defined in a geometric space, along with tools for querying and analyzing spatial data (Diakakis et al., 2019; Kulawiak & Lubniewski, 2014). For example, Damalas et al. (2018) used a geo-database for their DSS that enables the integration of geographical details of elements in different layers and hazard data models. Object-relational or object-oriented database systems have been used to manage complex data types (e.g., text, multimedia, image, and spatial stemming from social media) (Peng et al., 2011). Static databases have been deployed for data that are stable over time (e.g., historical data) and researchers have used dynamic databases for data that are continuously changing (e.g., operational data) (Schempp et al., 2019; Yang et al., 2012).

To foster implementation of digital initiatives, researchers draw attention to the potential for *leveraging cloud computing* (e.g., Clark & Guiffault, 2018; Ujjwal et al., 2019; Wilkinson et al., 2015), which provides "on-demand and elastic access to an almost unlimited storage, network, and computational resources" (Ujjwal et al., 2019, p. 2), and thus addresses the challenges of data, compute, and concurrent-access intensiveness in the deployment of, for example, geospatial models. It also responds to interoperability issues, as cloud services (i.e., infrastructure-, platform-, or software-as-a-service) can be deployed as a private, public, or community cloud offered to users. For instance, Zhao et al. (2018) developed Urban Safety, a mobile app for collecting urban disaster information, such as destroyed or damaged infrastructure. The app stores and integrates socially sensed data (e.g., images, questionnaires) in a cloud-based data repository.

Open access initiatives and *policies* for using online platforms to share data in public repositories increasingly inform DM activities. Access to these data sets and platforms is a valuable resource for developing repeatable, open, transferable, and cost-efficient DM approaches (Ruckelshaus et al., 2020). This stands in contrast to traditional practices, in which official reports on disaster impacts and dynamics are produced mainly for internal use (Luokkala et al., 2017). Examples of public DM databases include the HURDAT hurricane database maintained by the U.S. National Hurricane Center, the IBTrACS project that provides global tropical cyclone and hurricane data based on numerous tropical cyclone datasets (Ruckelshaus et al., 2020), and the global disaster database EM-DAT that provides data on various disasters worldwide.

Data sharing capabilities

Data sharing capabilities are key to effectively share data among a network of responders. To enable informed decision making and collaboration as a situation unfolds, responder organizations rely on task-critical information such as precise locations within the scene, information on hazardous conditions, injury and casualty data, and response tactics and progress among responders. A lack of interoperability and limited compatibility of systems are challenges for DM (Anson et al., 2017; Ujjwal et al., 2019). Incompatible data formats and a lack of interfaces between several information systems from different responder organizations can make it difficult to share critical situational information (Luokkala et al., 2017).

To support collaboration among responder organizations during a response, capabilities such as *data modeling* are key to standardization and exchange of information. Responder organizations may use heterogeneous systems that are independently managed and operated, so *flexible* data models have been proposed for standardizing information exchange among responder organizations (Chen et al., 2008; Chen et al., 2013). Chen et al. (2008) propose an XML-based data model that allows agencies at the local, state, and federal levels to leverage their existing information systems to participate in a national information-sharing ecosystem at only a minimal cost to retrofit existing systems and databases. The model design is platform independent and, hence, the organizations can incorporate a translation mechanism between their heterogeneous databases and the messaging infrastructure to map incoming and outgoing messages in accordance with data standards. No agency is required to alter either its legacy systems and databases or how it currently does business, while the model opens possibilities for data exchange with other agencies.

Developing standards and ontologies should also contributes to establishing shared DM vocabulary for transferring or providing data in a machine-readable structured form (Poblet et al., 2018), as well as data interoperability among different responders (Chen et al., 2008; Valecha, 2019). Such vocabulary formalizes the properties of key DM concepts (e.g., situational awareness, critical infrastructure, command and control) and the relationship among them. Ontologies are important to effectively integrate unstructured data (e.g., from social media) (Luokkala et al., 2017), develop novel DM systems (e.g., mobile applications), and overcome issues that arise when DM stakeholders use different terminology.

Multi-stakeholder information sharing platforms have been developed for sharing data effectively among different organizations and individuals in DM and thus enable collaborative decision making. Examples of such platforms include non-public web-based environments such as shared systems and databases among responder organizations and public ones such as CrowdCrafting or GeoTag-X (e.g., Ai et al., 2016; Dorasamy et al., 2017; Poblet et al., 2018). For instance, Aye et al. (2016) propose a web-based decision support system (DSS) for collaborative risk management in the context of floods and landslides. Their prototype provides a shared access point to information gathered by different stakeholders, enhancing access and dissemination of disaster-related data. This, in turn, allows all stakeholders to participate in the assessment of areas at risk, estimating potential damages or losses, and so on, based on all data available on the platform. These assessments and suggestions (e.g., review design of buildings in high-risk areas) can then be shared with other users to propose risk reduction initiatives. The system enables users to rank initiatives, display results that factor in users' roles (e.g., moderator, expert, decision maker), areas of expertise, and the organizations they work for (e.g., land management planners and civil protection). Continued engagement of all stakeholders, particularly because training may be required and organizations may already have different forms of collaborative decision making in place, are challenges in the effective use of multi-stakeholder platforms.

Information dissemination and alerting capabilities

Information dissemination and alerting capabilities refer to the ability to disseminate disaster-related information to the affected public. The literature emphasizes the use of multi-channel alerting and social media communication.

Responder organizations and authorities are responsible for disseminating disaster-related information (e.g., warnings, evacuation) to the public; today they use multiple digital communication channels such as social media (Ai et al., 2016), sirens, TV, radio, and mobile apps (Tan et al., 2017). The proliferation of smartphones led authorities and responder organizations to develop specific disaster apps (e.g., FEMA, the American Red Cross app, and more recently, Covid apps) as communication channels between them and the public (Fischer-Preßler et al., 2021; Tan et al., 2017). While channels such as social media and apps are on the rise for disseminating disaster information, the use of more traditional channels such as radio, TV and SMS (or Cell Broadcast) remain critical for several reasons, including (among others): the public may not perceive newer channels as their main source of disaster-related information from authorities; digital novices may not use them at all; trust issues may create challenges for effective disaster communication; and disaster-related rumors may spread on social media (Feldman et al., 2016; Zhang et al., 2019). It is, hence, crucial that authorities understand the channels the public uses and trusts and establish communications strategies accordingly (Feldman et al., 2016).

Systems and platforms that enable dispatching warnings via apps and traditional channels (e.g., sirens, TV, radio) are crucial. Sasaki and Kitsuya (2021) provide an example of an IT-configured community information dissemination tool. They developed a system that enables responders to reach elderly people through warnings dispatched to digital speaker devices. The German warning system (MoWaS) is a prime example of a digital configuration of information dissemination: it is modular, allowing for communication channels to be added; it incorporates the servitization concept, with access by multiple organizations with responsibility for dispatching warnings; and it relies on private and public infrastructure such as mobile phones and the internet.[5]

Increased use of social media shifted authorities to use it for disaster-related information dissemination. While the dispatching authority controls information flow in dedicated communication channels, that is not the case with public channels such as social media, where anyone with internet access can contribute unverified and incorrect information and rumors can easily spread (Oh et al., 2013). This fundamental aspect of social media is widely discussed by researchers (e.g., Mirbabaie et al., 2020; Oh et al., 2013; Reuter et al., 2018). For authorities, this means that beyond just understanding the public's need for information about taking protective measures, authorities must also understand the public disaster-related social media discourse so they can address potentially incorrect information and stop its propagation. For this reason, some research has focused on understanding the public discourse in disaster-related social media communication. For instance, Deng et al. (2020) present an interactive topic modeling approach that enables authorities to extract from social media the public discourse about an ongoing disaster and adapt their strategies for information dissemination via social media accordingly.

Analytical capabilities

Effective integration of data analysis activities in DM is a strategic imperative given the paradigmatic shift spurred by data-intensive disaster response (Bunker et al., 2015). DM tasks such as risk assessment of natural disasters increasingly build on quantitative modeling approaches—for example, by calculating losses and damages to infrastructure and people (Ruckelshaus et al., 2020). Like the other capabilities discussed so far, analytical capabilities are not always "digital." Take damage assessment, for instance: researchers have discussed how convolutional neural networks can be trained to classify roof damage after an earthquake. In one study, an AlexNet model was trained with annotated aerial images of the disaster area taken by drones, where the annotation involved labeling damaged and undamaged roofs (Fujita & Hatayama, 2021). Those annotated data were used to teach the algorithm to classify roofs as damaged or undamaged followed by visualization on a map to help the government coordinate resources more effectively. The annotation, however, remained a manual task, and access to experts or volunteers for manual annotation of images is critical to retrain models and achieve adequate accuracy (e.g., Beedasy et al., 2020; Fujita & Hatayama, 2021; Mangalathu & Burton, 2019). While trained models can be reused, visual cues of damage may remain context-specific, such as the use of blue sheets to cover what were likely damaged roofs in Japan (Fujita & Hatayama, 2021). Damage assessment capabilities are, however, likely to evolve into digital

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[5] https://www.bbk.bund.de/DE/Warnung-Vorsorge/Warnung-in-Deutschland/MoWaS/mowas.html (accessed May 28, 2024).

capabilities as analytical models become accessible as servitized solutions.

Data visualization capabilities

Data visualization is the capability to translate DM data into visual information objects. Here, the literature focuses on accessible visualization of DM data, developing geospatial visualization, and the visualization of simulations.

Data visualization typically configures as an IT capability. The extent to which data visualizations support decision making is an indicator of the level of development of data visualization capabilities. In disaster warning, the public is the intended audience. For instance, in a tornado warning message, interpretation of the visuals included therein (e.g., track forecast cone) is the most important driver of individual response to a tornado warning (Schumann et al., 2018). Also, professionals depend on visualization capabilities. For instance, the ability to choose effectively between 2D and 3D visualizations to solve a spatial task in disaster response is crucial for effective decision making (Shen et al., 2012).

Another example of data visualization is the development of geospatial visualization products such as digital maps, which respond to the demand for characterizing disasters spatially (Chen et al., 2016; Shen et al., 2012; Wang et al., 2019). In a study of a web GIS service for landslide response, scholars noted how data visualization initiatives are powered by a collaborative environment that integrates data across government organizations at multiple levels (e.g., local, regional) (Chen et al., 2016). That initiative was enabled by programmatic interfaces to invoke data assets (e.g., geological surveys) from institutional entities (e.g., Bureau of Surveying and Mapping). At the same time, programmatic access is not always reliable because the underlying application program interfaces (APIs) of external web services can change over time (Chen et al., 2016). For instance, in social network analysis, particularly on social media, visual network methods help reduce high-dimensional data to fewer salient dimensions for visualizing patterns in social media interaction, such as in network graphs, topic modeling, and timelines. Such analysis helps in understanding the disaster-related discourse of social media users during disaster events and the network structure of that discourse (Beedasy et al., 2020; Mirbabaie et al., 2020).

Data visualization based on simulation allows for testing scenarios and strategies in a controlled environment without real-world risks. Song et al. (2013), for instance, developed a crowd simulation for a bioterrorism event using a 3D visualization of the Olympic Park station of the Beijing Metro line 8 as a study area. This simulation modeled emergent behaviors in bioterrorism, such as queuing and herding, and thus informed DM decision making. Simulations may also trigger organizational transformation. For example, the Simulation of Transient Evacuation and Pedestrian Movement (STEPS) "helped engage regulators with new practices, overcoming their preference for precedent and repetition in design" (Dodgson et al., 2007, p. 860).

Supporting IT and digital capabilities

Supporting DM capabilities can help create digital initiatives. In this regard, the literature mentions crowdsourcing, training, and IT project skills that enable either the development of DM capabilities (e.g., through training) or the sourcing of them (e.g., from the crowd).

Crowdsourcing capabilities

Crowdsourcing is the harnessing of technology to source resources from the public to support DM activities. Crowdsourcing is an effective way to support data processing capabilities, especially for subdividable tasks, by outsourcing to the crowd tasks that require human skills, programming, design and development, skill-based talent search, or fact-checking (Callaghan, 2016). We have identified three main roles that the crowd serves in DM: public-as-reporters, public-as-microtaskers, and public-as-developers.

Crowdsourcing can support social sensing (Kankanamge et al., 2019; Luokkala & Virrantaus, 2014; Poblet et al., 2018; Yuan & Liu, 2018). In the *public-as-reporters* paradigm, authorities leverage users' physical presence to collect first-hand, real-time information to support early warning (Carley et al., 2016); track the status of disasters as they unfold, as in tweeting about a hurricane making landfall (Ogie et al., 2018); or even for damage assessment in the recovery phase (Khajwal & Noshadravan, 2021; Yuan & Liu, 2018). The public becomes an active participant in real-time disaster communication and reporting from the scene (Kankanamge et al., 2019), increasing hyper-local situational awareness and improving localized disaster response. Social media, disaster-specific open access platforms (e.g., Ushahidi), and dedicated mobile apps to crowdsource disaster-related data (Shen & Shi, 2019; Tan et al., 2017; Zhao et al., 2018) are examples of channels that enable the public to serve in this "reporting" role (Poblet et al., 2018; Riccardi, 2016).

Earlier we discussed social media as enablers of social sensing, but here we stress their role as channels for sourcing preprocessed data. For example, using hashtags allows for user-generated content classification (i.e., folksonomy), which constitutes rudimentary structuring and preprocessing of disaster-related data. Similarly, dedicated crowdsourcing apps such as Urban Safety enable the public to collect data on the state of urban infrastructure, using questionnaires and photographs, and share those data with authorities for disaster prevention and mitigation (Zhao et al., 2018).

In the *public-as-microtaskers* paradigm, the public performs small DM tasks, such as those related to processing raw data. To assess roof damage, for instance, images could be labeled by government staff or crowdsourced (Fujita & Hatayama, 2021). Recruiting microtaskers among the population allows scaling annotation of large amount of data quickly: by labeling images, adding coordinates, and tagging reports to disaster categories, the public can generate structured and high-quality data that emergency responders can use to coordinate their activities. Crowdsourcing annotators, however, raises questions about the accuracy of annotations as they may lack adequate training, as well as accountability for incorrect annotations. Ultimately, this calls for authorities to address the tradeoff between quantity and quality. There are organizations today that offer digital humanitarian services, including MicroMappers (combining crowdsourcing with machine learning), Standby Task Force (organizing digital volunteers into networks; offering an interface for the humanitarian community), Humanitarian OpenStreetMap Team (applying open source and open data sharing for disaster response and economic development), and Digital Humanitarian Network (consortium formation of volunteer and technical communities) (Callaghan, 2016).

Finally, in the *public-as-developers* paradigm, digital volunteers have been recruited for coding tasks in DM. Campaigns such as #Hack4Good and Geeklist Corps of Developers have recruited volunteer coders, product managers, and other technical experts from around the world to develop web-based platforms to help coordinate rescue efforts (Li et al., 2013), enable disaster communication (Poblet et al., 2018), and support spatial planning in disaster recovery (Mejri et al., 2017). Open source and open access software initiatives allow crowd-driven modification and adaptation of software (Li et al., 2013) in a collaborative effort to contribute to software as a public good. Code that is publicly visible and modifiable also fosters trust in the system. Ushahidi and Sahana, along with several contact tracing apps, are examples of specific DM software developed under the free and open-source software paradigm. OpenStreetMap is an example of a collaborative, open-sourced mapping platform used in DM systems (Ruckelshaus et al., 2020).

Technology-enabled training capabilities

Technology-enabled training uses digital data and tools for organizational learning. Training is defined as a capability—albeit only a *supporting* one—because the ability to deliver effective technology-enabled training can configure as a resource itself. For example, virtual and augmented reality technology enable effective, flexible, and affordable training platforms for different disasters (Lovreglio & Kinateder, 2020; Oe & Kawakami, 2021). Virtual reality (VR) provides trainees with immersive interfaces (objects, tools, utensils, etc.), although longstanding concerns pertaining to the realism and, in particular, the physicality of certain tasks (e.g., shutting down engines, applying first-aid techniques) remain unaddressed. Nonetheless, immersive reality has always been considered a sound means to effectively train skills such as finding escape routes through a smoky building and finding locations of hydrants (Beroggi et al., 1995). Prior research argued that some of the advantages of virtualizing traditional evacuation drills using VR (head-mounted display technology) are that VR-simulated drills are more cost effective (when developed at scale), less risky, accessible to mobility-impaired individuals, and facilitate more granular and systematic data collection (e.g., about evacuation behavior). However, they are less realistic and narrower in scope than traditional drills, since they only simulate one scenario, and hence may be insufficient to satisfy regulatory policies (e.g., ISO 14001, Clause 4.4.7) for required evacuation drills (Gwynne et al., 2020).

Technology-enabled simulation allows for reproducing educational sequences for developing, redefining, or consolidating capabilities. Simulations present fictitious scenarios for practicing skills for which an immersive experience is not crucial (Tena-Chollet et al., 2017). A main benefit of virtual simulations is they allow for breaking down a scenario into its constituent learning opportunities and designing the simulation to pursue specific learning objectives. Inter-organizational communication, for example, as well as several capabilities discussed earlier in this paper, can be trained or tested using virtual simulations. In short, simulations can serve as boundary objects to foster technology-related initiatives through “shared imagining” of different organizations involved (Dodgson et al., 2007, p. 859).

IT project development/management capabilities

IT-project development and management capability is the ability to successfully develop and implement IT and digital initiatives. Research suggests that known project management approaches may work well in the DM context. For instance, the agile development cycle was found effective in the development of Local EVOp Flooding Tool (LEFT), an extension of the Environmental Virtual Observatory pilot (EVOp) project involving a multi-disciplinary working group of hydrological, environmental modeling, social science, distributed computing, and programming specialists. Agile development allows adaptive planning through evolutionary steps, with continued stakeholder collaboration, thus facilitating rapid and flexible response to change. This was critical, as the project required several iterations with key stakeholders throughout the project cycle to ensure the tool would meet users’ needs (Wilkinson et al., 2015).

The ability to follow *user-centered design* principles is an example of an IT-project development capability. For instance, designing effective disaster risk visualization is a challenge due to the heterogeneity of end users and different disaster contexts. To tailor visualization to end users, it is crucial to elicit their requirements and feedback during the design process, their feedback during prototyping, and then when refining the prototype in that end-user context (Twomlow et al., 2022).

Authority-driven and public-driven initiatives

We identified two main drivers of IT-enabled and digital initiatives, authority-driven and public-driven, which we discuss in the subsequent sections.

Authority-driven initiatives

Authority-driven initiatives are typically initiated in *preparation* for, but sometimes also in *response* to, a disaster. They show DM as primarily the responsibility of public authorities. They are managed by the government or other public responder organizations (e.g., high-reliability organizations) and can be sponsored at different levels (e.g., local, state, national, international) (Youngblood & Youngblood, 2018). The scope of such initiatives can vary significantly since, depending on the processes they support, they can involve different levels and stakeholder groups.

Two types of authority-driven initiatives stand out in the literature: *national* and *local*. *National* DM initiatives involve a multitude of stakeholders and typically address the support of DM activities that scale nationwide (e.g., national warning system, Covid-19 contact tracing). As DM is multi-organizational and hence, a highly collaborative system (AlHinai, 2020), digital initiatives must consider the interests of multiple stakeholders. Hence, while authorities are leading the initiative, it depends on the exchanges of interests with other stakeholders such as infrastructure, transportation, hospitality, and the public (AlHinai, 2020).

Local initiatives are under the purview of local authorities focused on the management of local or regional disasters. They often lead to producing resources that are tailored to the needs of the community they serve. Such community-specific needs can be dictated by the types of disasters that affect a region, such as flooding in flood-prone areas, wildfires in forested regions, or chemical accidents in locations with chemical plants. The effectiveness of such local initiatives may depend on unique socio-technical factors such as population density and distribution, demographics, and IT infrastructure. This means the value of a resource remains high only if it is deployed for the community it was designed to serve. Multiple initiatives identified in this review, especially those related to risk assessment and local rescue activities, appear to provide solutions for local communities: these include, for instance, an early warning and evacuation systems for Padang, Indonesia (Ai et al., 2016); a flood alert system for the Mushim stream in Korea (Azam et al., 2017); and a GIS for planning shelters, evacuation routes, and shelter zones in Futian, Shenzhen, China (Jiang et al., 2018). For local initiatives like these to become digital ones, they must be developed as adaptable for use by local authorities elsewhere that face similar disasters.

Most IT-enabled and digital authority-driven initiatives we identified in this review were developed to *prepare* for disasters. These include, among others: disaster apps (Tan et al., 2017), risk management systems (Ruckelshaus et al., 2020), geographical information systems (Aye et al., 2016), and decision support systems (Ai et al., 2016). Some initiatives, though, are initiated in the midst of disasters, when existing response strategies prove inadequate—often because the disaster's scale is unprecedented or preparation was inadequate. In these instances, the rapid development of new IT-enabled or digital solutions becomes crucial for effective disaster response, as exemplified by the global digital efforts to address Covid-19 (Budd et al., 2020). Table 5 shows the dimensions of local and national disaster preparedness and response initiatives by authorities.

In the following sections, we illustrate examples of authority-driven IT and digital initiatives.

Authority-driven IT-enabled initiatives leverage IT resources to support the execution of DM tasks. Examples include firefighters adopting digital plans and guides, on-site emergency response information systems, ground robots, intelligent protective clothing, and unmanned aerial vehicles (Weidinger et al., 2018).

Many of the models and tools developed are not yet configured as digital resources but may be in the future. For instance, as discussed earlier, Fujita and Hatajama's (2021) roof damage assessment capabilities through deep learning are currently based on context-specific visual cues of damage that require domain knowledge and human labeling but may be developed in the future into a digital resource that can be reused programmatically.

In addition, we consider initiatives that leverage social media data—for example, from Twitter—to be IT-enabled if they "tend to be one-off and have little reuse" (Landwehr et al., 2016, p. 2) or do not generate digital resources. For example, Landwehr et al. (2016) examine TWRsms (Tsunami Warning and Response Social Media System), a module designed to be part of larger system for tsunami warning in the community of Pandang, Indonesia. TWRsms enabled access to tsunami-related Twitter data through a webpage that provided live access to Twitter feeds, the analysis of those feeds, and the historical data along with the analyses of past tsunami events. However, the webpage was not designed to provide access to their data repositories through programmatic interfaces—a necessary condition for a data asset to be "digital."

Authority-driven digital initiatives are strategic actions that build on digital resources to enhance governmental and public responder organizations DM capabilities. One example is the platform for landslide risk management discussed in Chen et al. (2016). The platform uses API access to integrate data assets from different governmental authorities such as the Bureau of Surveying and Mapping[6] and the Bureau of Meteorology (e.g., rainfall data) to inform 2D and 3D WebGIS models for landslide management. In such multisource data environments, API access to original data repositories is key to having the most current data and ensuring consistency. The authors warn, however, of the risk of relying on external web services, as changes in the underlying API interface may create compatibility issues that necessitate updates or platform modifications. This research underscores the importance of articulating the architectural and organizational requirements that enable using digital resources consistently and reliably to support DM functions. Such ability to provide sustainable and reliable solutions, rather than temporary or one-off ones, is key to achieve DT.

Public-driven initiatives

Public-driven initiatives are led by members of the public, such as local communities and digital volunteers. Typically, the role of the public emerges in response to a disaster, often to remedy the lack of adequate help from the authorities. Public-driven initiatives rely on local communities' knowledge of their social context, vulnerabilities, and needs. Compared to authority-led initiatives, the scope of public-driven initiatives focuses on a limited set of DM functions. In the literature, the public-driven initiatives most typically pertain to self-organizations of local communities and crowdsourcing. Self-organization is enabled by social media and is mostly enacted in the aftermath of a disaster (Tim et al., 2017). Self-organized entities tend to be ephemeral, that is, brought together by the urgent need to cope with a disaster, but they tend to dissolve as the population recovers from the event.

Self-organizing relies on informal networks of community members, either preexisting or formed in response to a disaster, and pursues the alignment of communication with immediate disaster response needs. Self-organizing can be crucial when conventional command systems are overwhelmed, such as during the 2011 Thailand floods, when social media bridged the communication gaps between disrupted communities and aided in orchestrating collective response efforts (Ling et al., 2015).

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[6] https://www.tianditu.cn/ (accessed May 28, 2024).

Table 5
Dimensions of Authority-driven DM Initiatives.

	Preparedness	Response
Local	Disasters for which causes and impacts are spatially interlinked at local scales (e.g., earthquakes, flood) require IT-enabled/digital initiatives to support specific local processes (e.g., risk management focusing on community vulnerabilities).	A disaster triggers the need for developing a new IT-enabled/digital solution, or adapting an existing one, to support ongoing local DM processes to cope with the disaster (e.g., local community-based IT-enabled/digital solutions to cope with Covid-19).
National	In preparation for disasters (e.g., natural disasters), national authorities establish longer-term nationwide initiatives that aim to support similar, nationwide processes of DM stakeholders at different levels and in regions (e.g., national warning system).	Large-scale disasters (e.g., Covid-19) trigger novel, rapidly developed nationwide IT-enabled/digital initiatives to support ongoing nationwide DM processes to cope with the event (e.g., contact tracing).

Table 6
Authority-driven and Public-driven Initiatives.

	Authority-driven	Public-driven
IT-enabled	Authorities initiate the development of DM systems that are based on IT resources and are under the organization's control (e.g., information and communication technology-assisted DM activities).	The public's use of social media in disasters leads to changes in disaster-related communication. Communities use digital technology, especially social media, to self-organize in response to a disaster.
Digital	Authorities initiate the development of DM systems that are implemented as a digital resource, incorporating tasks/processes of and access from several stakeholders (e.g., the German nationwide warning system MoWaS).	The public initiates the development of digital platforms (e.g., Ushahidi) that support disaster-related activities (e.g., crowdsourcing of public reports in disasters).

Self-organizing via social media (e.g., Ling et al., 2015; Tim et al., 2017) may serve as an example of a *public-driven IT-enabled initiative* because it repurposes public social media platforms and messaging apps using personal devices such as smartphones for ad-hoc DM response. Nonetheless, social media self-organization can redefine the identities of both communities and authorities. For example, the use of social media during the floods in Thailand broadened connections among community members—including victims, volunteers, professionals, community leaders, and universities—thereby fostering a sense of empowerment in local communities and independence from the help of the authorities (Ling et al., 2015). While our theoretical background initially suggested that IT-enabled transformation tends to reaffirm an organization's already established identity, this shows IT-enabled initiatives are still capable of redefining organizational identity. It implies that initiatives that are not "digital" as per Piccoli et al.'s (2022) definition, particularly those using social media, have the potential to present some of the organizational transformation aspects typically attributed to DT.

For *public-driven digital initiatives*, we identified the crowdsourcing web-based platform Ushahidi. The increasing access to digital resources by local communities not only enables digital initiatives, but also effectively turns the public into one of their primary sponsors. In 2008, volunteers developed Ushahidi to monitor and map political violence after the elections in Kenya. It was created quickly, in contrast to the often lengthy, structured process of formal software development. Its modular and open-source architecture allows for deploying maps to support different types of disasters such as the 2010 earthquake in Haiti, where volunteers used Ushahidi to manually map thousands of requests for help collected via SMS (Riccardi, 2016).

At present, Ushahidi provides API access that, together with its modular architecture and the social value of information it gathers, manifests Ushahidi as a digital resource. For example, "Ushahidi can be configured to work with Twitter API and provides APIs for data exchange in XML and JSON" (Saroj & Pal, 2020, p. 9). The API does not only make Ushahidi disaster data "visible [to] and exploitable [by]" the public—a key characteristic of digital initiatives—but it also contributes to "generating a historical memory of the crisis" (Mejri et al., 2017, p. 50). Table 6 summarizes examples of authority- and public-driven initiatives.

Value generation through IT-enabled and digital initiatives in disaster management

From our literature review, we identified two main areas in which initiatives generate value: generating operational and public value and learning.

Generating operational and public value in disaster management

Value in DM is above all about saving people's life, and virtually all initiatives aim to reinforce that value proposition, as expressed in DM's main functions: mitigating, preparing, responding, and recovering from disasters. In this sense, technology can generate *operational value* by exposing resources (e.g., data, labor), partially automating processes, enabling connectivity, and informing assessment and decision making to support all DM functions. For instance, for disaster *mitigation*, crowdsourcing apps such as Urban Safety enable the public to collect and share data (social sensing) with authorities (connectivity) on the state of urban infrastructure; authorities can use these data for disaster prevention and mitigation (decision making) (Zhao et al., 2018). In *preparation* for disasters, a local early warning and evacuation platform for a community exposed to tsunamis developed by Ai et al. (2016) provides an example. The DSS incorporates features to analyze data from a sensor-based undersea infrastructure for early warning of responders (access to resources), a social media component to disseminate warnings to the community (connectivity), and a digital map feature with routes to and capacity of emergency shelters (decision making).

An example in *response* to a disaster is digital contact tracing during the Covid-19 pandemic, which allowed for automatic tracing of encounters between app users (social sensing), typically using Bluetooth. Users receive a warning via the app (connectivity) that they might be at risk of infection if they have been close to another user diagnosed with Covid-19 for an epidemiologically relevant time interval within a relevant timeframe (automation) (Trang et al., 2020). For disaster *recovery*, the algorithm for roof damage assessment after earthquakes, discussed earlier in this paper, is an example. The algorithm takes physically sensed data (resources) to classify damaged and undamaged roofs, partially automating processes because governments do not have to send experts to assess damage. This helps governments coordinate resources more effectively (decision making) (Fujita and Hatayama, 2021).

Several articles implicitly appraise *public value*—the "value" of an initiative reflected on the public—generated by initiatives. For example, during Hurricane Sandy, the use of Twitter by the New York Fire Department enhanced the department's reputation and increased public appreciation and trust for its work, thereby creating public value (Chatfield & Reddick, 2018). In the context of public value, the construct of "group value" in DM must be mentioned. Group value may indirectly generate public value, as it measures the extent to which a system will improve the collective response of all participating responder organizations to a flood (Lee et al., 2011). In the context of public value, the construct of "group value" in DM must be mentioned. Group value may indirectly generate public value, as it measures the extent to which a system will improve the collective response of all participating responder organizations to a flood (Xu & Tang, 2020). Identifying forms of value of DT for DM is crucial, as it provides arguments and motives for developing and funding digital initiatives for DM.

Opportunities for intra- and inter-organizational learning

Organizational digital capabilities can serve as enablers for organizational learning, which is a crucial aspect in continually improving DM activities. Organizational learning comprises a cycle of acquiring new knowledge (understanding real-time updates from social media or sensor data), retaining that knowledge (developing better analysis tools and predictive models), and transferring it (sharing insights and strategies with other organizations) (Argote et al., 2021).

Research identified two types of learning in DM: *inter-disaster learning*, that is, learning from disasters to prepare for future events; and *intra-disaster learning*, that is, learning during a disaster (Moynihan, 2009). Different initiatives enable different forms of learning. For instance, research on organizational learning in DM shows that community self-organization (public-driven IT-enabled) provides opportunities for intra-disaster learning through opening organizational and public resources (such as information, knowledge). Making resources accessible in disaster response enables novel modes of collaboration among and between stakeholders from responder and emergent organizations who build and expand upon the exchange of such resources (Eismann et al., 2021).

Such efforts may be only a one-time reaction of the community to immediate disaster response needs, presenting opportunities for intra-disaster learning alone (Eismann et al., 2021). Social sensing can also become an opportunity for inter-crisis learning. For instance, socially sensed data retained from an initiative can become new knowledge and be used for developing methods to filter and analyze social media data during future disasters.

Risks and challenges in data sensing and processing

Determining whether and to what degree IT-enabled and digital initiatives yield value, as defined earlier, raises questions about possible harmful consequences of sensing and processing initiatives. We elaborate on such risks and challenges hereafter.

Data injustice refers to inequities that arise when data generated by digital technologies unfairly represent certain groups of individuals or that data is limited in volume, variety, and velocity in certain regions, such as developing countries (Chandy et al., 2017). Patterns of missing data may reveal a systematic inability to collect data about the status of certain groups in disasters. For instance, the poorest people, who are often hit the hardest by a disaster, are underrepresented in social media data (Baytiyeh, 2018). In fact, there is a risk that the data do not represent people equally well, underrepresenting lower-income people and digital novices. For instance, a study of social media data from 2017's Hurricane Irma in Florida revealed that affluent coastal communities were much better represented than poorer inland areas (Forati & Ghose, 2022). Such biases may compromise the validity of analytical methods that make inferences based on social media data, distort situational awareness, and lead to underestimation of the needs of segments of the public (Dargin et al., 2021). A similar study in Florida after 2018's Hurricane Michael, however, showed that numerous 311 service requests for power restoration using the mobile app "DigiTally" came from poorer communities, indicating that the digital divide might be driven by age disparities rather than income or racial differences (Xu & Tang, 2020).

Disaster data are often incomplete, costly to collect both in time and financial terms (Ozguven & Ozbay, 2013; Ruckelshaus et al., 2020), and/or difficult to interpret (Rautela, 2016; Sarker et al., 2020). *Insufficient data quality* is frequently mentioned as an issue with socially sensed data (Chandy et al., 2017; Sarker et al., 2020). Understanding and identifying limitations in data quality is critical, as it helps in assessing when the potential value of an initiative may be limited by low data quality or when an initiative may even be detrimental because data are incorrect and misleading. Organizations need mechanisms to verify the accuracy of disaster data and ensure that dependable information can be generated from those data. For instance, experts should assess data quality to ensure accuracy before the data are permanently stored in an organizational database (Zhao et al., 2018). For social media communication in disaster response, timely suppression of rumors and false information is critical to avoid social reporting from degenerating into collective rumor mills (Oh et al., 2013).

Researchers studied different *privacy* and *data protection* issues, particularly when the data come from social sensing. Systems that could collect sensitive data may not be used or may not be useful in DM because of privacy concerns. For instance, contact tracing apps are effective only if a certain number of people install them on their smartphones (Rowe et al., 2020; Trang et al., 2020), but these apps may raise concerns that data initially collected for the public good might be used for mass surveillance (Ribeiro-Navarrete et al., 2021). This dilemma poses a significant challenge, as the utility of such systems in DM is closely tied to public trust in how their data are managed and protected.

Leveraging digital technology in DM adds new layers of *vulnerability to critical infrastructure*, which encompasses all the assets (e.g., the electric grid, telecommunication, hospitals), systems, facilities, and networks that are crucial for society to maintain its vital functions, as well as the health, safety, security, economic and social well-being of people (Gromek, 2021). Infrastructural properties cannot be presumed to remain stable during a disaster, but digital technologies rely on a functioning critical infrastructure and failures of the electric grid or network might disrupt DM capabilities, such as disconnecting the population from communication channels or limiting responders' organizations access to cloud-based tools (Anson et al., 2017; Pescaroli et al., 2018). Similarly, sensors may be destroyed by a disaster and disrupt sensing capabilities, limiting the application of data- and computing-intensive methods (Ozguven & Ozbay, 2013) and the maintenance of the data ecosystem.

Earlier in this paper, we characterized digital initiatives as those that thrive in modular, infrastructural, and combinatorial technological ecosystems (Piccoli et al., 2022). The DM literature highlights several challenges in such "digital" ecosystems, particularly with respect to systemic risks. The modularity and combinatorial properties of digital resources imply that digital initiatives bear several dependencies (e.g., AlHinai, 2020; Forati & Ghose, 2022; Oh et al., 2013; Pescaroli et al., 2018). These properties can also be leveraged by malicious actors to trigger cascading failures, such as by manipulating communication and information (e.g., hacking, spreading rumors) or attacking critical infrastructure (e.g., cyber-terrorism, creating cybersecurity issues) (AlHinai, 2020; Anokhin et al., 2021). In efforts to make critical infrastructure more reliable, researchers have adapted military technology originally developed for ranking the attractiveness of potential targets (i.e., CARVER2) to assess the risk profile of elements of the critical infrastructure. Moreover, they have called for models that can incorporate multi-asset, multi-layered, and geographically distributed critical infrastructures rather than just one specific asset (e.g., the power grid) (Kulawiak & Lubniewski, 2014).

Discussion

Our research makes two major contributions. First, we provide an overview of research in the interdisciplinary field of DT in DM. Our framework (Fig. 1) provides researchers with a synthesis and contextualization of areas of research from 254 articles in six different fields. We identify a set of DM capabilities necessary for implementing IT-enabled and digital initiatives as well as their positive and negative outcomes. In this way, we address the fragmented state of research on DT in DM and take a step toward the development of a common set of concepts to integrate future research across disciplines.

The second contribution pertains to characterizing DT in the DM context and distinguishing between "DT in DM" as opposed to merely "using digital technologies in DM." We do so by distinguishing between digital and IT-enabled initiatives among those studied in the articles in our sample, presuming that digital initiatives are preludes to DT. This distinction was difficult to make in some cases, because studies typically focus on a specific technology (e.g., ML) or phenomenon (e.g., self-organization) rather than the broader effects of digital technologies on organizational culture, the development of "digital" architecture (i.e., modular, accessible programmatically), and the larger digital ecosystems in which specific technologies thrive. Nonetheless, distinguishing DT from IT-enabled initiatives shows how using what is commonly referred to as "digital technology" in DM does not necessarily morph into—and fully leverage the attributes of—digital resources as defined in Piccoli et al. (2022). In practice, the distinction between IT-enabled/digital conceptualization is helpful for understanding the additional value and risks of implementing technology-related initiatives as truly *digital* ones.

Scope of digital transformation in disaster management

The DM literature has a clear focus on how digital technology can "sense" (sensing capabilities) and "make sense" (processing capabilities) of the real world to support disaster mitigation, preparing, responding, and recovery. In industry settings, the focus is on the disruptive nature of digital technologies and the changes they initiate in value-creation paths. The initiatives we surveyed appear, instead, to support existing DM capabilities and the pre-existing "business model." None of the authority-driven initiatives we identified—not even the "digital" ones—fundamentally transformed or disrupted the DM industry as a whole (Vial, 2019), redefined organizational identity (Wessel et al., 2021) or morphed an organization into being "digital-first" (Baskerville et al., 2020). In terms of authority-driven digital initiatives, we encountered challenges in pinpointing noteworthy instances of organizational restructuring—although, admittedly, our inability to identify major organizational changes may be because the articles we examined did not necessarily focus on studying organizational transformation.

We did not find instances of organizational transformation, nor were we able to articulate the effects of digital initiatives on responder organizational structures, processes, and identity. This may suggest that organizational changes occur incrementally, perhaps driven by a series of initiatives that are tested and integrated within organizations. The cumulative effect of these initiatives may eventually digitally transform an organization by redefining its organizational identity and value proposition.

Scholars have, though, begun to question whether observing organization-wide transformation is a necessary condition to identify DT or whether DT can instead be bounded within specific "business units, organizational functions, or focus" (Piccoli et al., 2024, p. 11). This suggests that the identifying properties of DT may be context-specific and transformations can be rightfully labeled as "digital" rather than IT-enabled even if DT unfolds at sub-organizational levels—such as departments or teams—with limited short-term impact on the overall organizational identity.

In addition, it is not uncommon in DM for the public to maintain its existing expectations and requirements even when technological developments create new affordances; so-called “digital volunteers” exemplify how the public actively contributes to build resources such as providing disaster related data. Public-driven initiatives, such as self-organization via social media, respond to the urgent needs of a community hit by a disaster. However, unlike in the industry setting, initiatives driven by the immediate need to respond to a disaster are not purposefully implemented to pursue long-term DT and may dissolve after that immediate need is met. This means that those initiatives are unable to trigger and maintain a sufficient degree of change both in the structure and culture of DM organizations.

Consider, for example, how some public-driven initiatives via social media enable communities to stay informed (Beedasy et al., 2020), self-organize (Tim et al., 2017), and cope (Ling et al., 2015) with disasters. These initiatives appear to disrupt or redefine societal organizational structures to an extent that truly seem to “chang[e] people and communities” (AlHinai, 2020, p. 11), but such transformations are sometimes ephemeral. Such initiatives may be effective in providing immediate relief or support and assisting in monitoring and reporting, but may also dissolve after a disaster. Hence, public-driven initiatives appear less likely to produce a lasting transformation, although they serve the immediate needs for intra-disaster learning (Eismann et al., 2021).

Public-driven initiatives also appear to manifest as *collective social actions* (Tana et al., 2023) with the potential to shift the locus of DT beyond DM organizations. In this respect, we note that some initiatives followed patterns identified in prior literature, where initiatives that began as temporary and limited in scope eventually transcended their initial objectives. Ushahidi, for example, began as project for monitoring political violence in Kenya but eventually was redesigned as a digital resource to support different types of disasters.

Sometimes ephemeral public-driven initiatives instill lasting beliefs about the role of technology in DM, such as the expectation that public authorities will monitor social media in the aftermath of a disaster. This is another reason to consider these initiatives as driving DT. From a strategic standpoint, this means that sustaining DT must include devising strategies not only to react to societal changes in technology-related behavior and expectations, but also to allow public authorities to synergize with public-driven initiatives. Digital technologies enable a population to support DM, for example, by generating socially sensed data; unlike physically sensed data, however, which typically fall within the scope of authority-driven initiatives, these data are rarely structured as a digital resource. We argue, instead, that the value of sensing initiatives, like those that retrieve disaster-related information from social media, increases when the data assets they generate are exposed and accessible programmatically, in line with the definition of being digital resources.

Digital transformation as a “response” to disasters

As Fig. 1 shows, some initiatives are driven by the urgency to respond to a disaster, thereby accelerating the development and implementation of initiatives in DM. This exogenous explanation of transformation in DM reflects the characterization of DT in the industry setting, where DT is a reaction to “disruptions” (Vial, 2019, p. 122) fueled by the use digital technologies. In particular, the use of digital technology alters the data availability and customer expectations and reshapes the competitive landscape, eventually prompting DT as a strategic response from companies (Vial, 2019).

The Covid-19 pandemic shows how immediate disaster response needs may prompt swift authority-driven initiatives, such as the deployment of contact tracing apps (Trang et al., 2020). However, it also demonstrates that rapid technology-driven initiatives do not necessarily lead to DT or bear the properties of a digital resource as conceptualized by Piccoli et al. (2022). For example, “contract tracing” was intended as a DM capability for Immuni, the Italian tracing app, but it did not constitute a digital resource because it could not be accessed programmatically. While the app alerted users of potential exposures, it left up to them whether to contact their doctor or local health authority to report exposure and begin the quarantine period. Health authorities lacked programmatic access to socially sensed contact-tracing data; hence that contact tracing did not constitute a digital resource. In this respect, contact tracing through mobile and Bluetooth technology emerges as an evolution of existing IT-enabled solutions rather than a capability that swiftly morphed into a digital one amidst the pandemic.

Using technology for contact tracing dates back to the response to the 2003 SARS outbreak in Singapore, for which Leidner et al. (2009) report two examples: a hospital that used radio frequency identification tags (RFID) for tracing contacts among patients; and the Ministry of Health-mandated installation of webcams in private homes and a requirement that individuals appear on these cameras upon request to prove their compliance with the quarantine order. The difference in scale between SARS and Covid-19 contact tracing is apparent, but the distinguishing properties of “digital contact tracing” (Karanasios, 2022, p. 860) and “development of ‘digital contact tracing 2.0’” (Karanasios, 2022, p. 870) remain unclear in comparison to earlier contact tracing initiatives. While Covid-19 brought the use of technology for contact tracing to the forefront, contact-tracing initiatives appear largely incremental developments of prior IT-enabled initiatives.

Outcomes of digital transformation in disaster management

In Fig. 1, our framework presents the outcome of initiatives as positive (value) or potentially negative (risk). In the industry-focused literature, “value” refers to financial or organizational value (e.g., through improvement of business outcomes, automation of tasks). DM, as does industry, benefits from some organizational value: we identified that organizations profit from operational value (e.g., automation of tasks, access to new resources) as one form of value through DT.

The value of digital resources in DM includes other under-researched forms of value in the current industry-focused DT scholarship. In particular, we identified forms of *public value*—value created for the public to guarantee “the best possible cohesion between the expectations of the [public] and the actual deliverables of the actions of the public administration” (Cordella & Bonina, 2012, p. 516). The public might expect that initiatives create value by fostering cohesion among communities in the aftermath of disasters or

Table 7
Opportunities for Research on Digital Transformation in Disaster Management.

Theme	Sub-theme	Example research questions
Developing capabilities	Focus on DM processes	What DM tasks or processes are suitable to be transformed in digital capabilities, and how can this be done effectively? How do the roles and tasks of DM professionals change when new digital capabilities are implemented?
	Co-creating and shared use of digital resources	How to effectively generate value from digital resources that encapsulate socially sensed data? This question may be answered by considering the channel (dedicated/adapted) and/or type of social sensing (participatory/opportunistic) as stressors. How can we enhance collaboration between communities and disaster management professionals through the co-creation of digital resources and their shared use?
	Development of micro-capabilities	How do supporting capabilities (e.g., crowdsourcing) drive the success of digital initiatives? What DM tasks can be supported by micro-tasking?
Entities undergoing transformation	Organizational change	How does the implementation of a digital initiative impact the organizational structure of responder organizations or trigger cultural shifts (e.g., embracing digital-first approaches, agile governance)? What cultural and organizational characteristics set apart organizations that successfully execute digital initiatives from those that struggle or fail to do so?
	Self-organization	How do self-organized communities that form in response to disaster situations evolve into sustained digital initiatives? How does organizational identity transform as initiatives develop from one-off, emergent ones into mature and structured digital initiatives? How can the morphing of public-driven IT-enabled initiatives into digital ones be supported?
Value and challenges of technology-related initiatives	Creation of digital public resources	How can the creation and leveraging of digital public resources be supported effectively? How can public resources that increase resilience of communities worldwide be developed?
	Privacy and ethical concerns	What ethical dilemmas and privacy concerns arise from the characteristics of digital resources (e.g., modularity) and their deployment in digital ecosystems? How can ethical integrity in digital ecosystems, digital initiatives, and digital resources in DM be maintained? What ethical principles support system design in DM?
	Secure “digital resources” for information sharing	How digital resources be shared securely between organizations in large disaster response networks? How can technologies better align information needs with information sources in diverse stakeholder networks?
	Infrastructural resilience and resilient design of digital resources	What resilient design principles should drive digital initiatives so digital resources are generated or recombined to function with minimal infrastructural support? To what extent can resilient design principles contribute to the digital inclusivity of regions with underdeveloped technological infrastructures?

portraying public authorities as vigilant and ready to intervene when there are disasters. These diverse forms of value are a function of the broader range of organizational structures of stakeholders which, in DM, are not limited to commercial entities. In the DM context, organizations can be non-governmental organization (NGOs), governmental agencies, or responder organizations (e.g., fire fighters, paramedics), as well as communities and self-organizing networks of local volunteers.

Future research agenda

Our review of the literature surfaced three major areas to consider for positioning research at the intersection of DT with DM. We propose these areas not only because they are under-researched, but also because they are critical for contextualizing the cumulative tradition in the DT discourse to DM, ultimately providing DM scholars with better theoretical tools, such as the notion of digital resource, to study technology-related initiatives to support DM. First, we call for focusing on conceptualizing the underlying DM process that a technology-related capability or initiative supports. This is critical to understand the transformative potential of digital initiatives on existing DM tasks and processes. Second, we call for defining the entity undergoing DT and how a digital initiative transforms its organizational structure. This is important to clarify the level of abstraction at which DT is observable—for example, is it an organization-wide phenomenon or can it unfold at a different scale? Finally, we call for conceptualizing the value generated or expected by deploying digital resources and the risks of technology-related initiatives. Table 7 provides examples of research questions for these three themes and their sub-themes. In the next sections, we elaborate on how to contribute to these three research areas.

Developing capabilities

Focus on disaster management processes

IS researcher may conflate how effectively technology-related initiatives are implemented with how effectively they can support DM tasks and processes. While disasters accelerate the implementation of such initiatives, their effectiveness in supporting DM tasks and processes may require a longer period of observation and a shift in focus from evaluating initiatives toward studying the value they create for the DM capabilities they are meant to support.

We broadly categorized technology-related initiatives in DM as either *sensing* or *processing capabilities;* however, we did not specify which DM task they support (e.g., situational awareness, fatalities management). In general, however, we conceive sensing and processing capabilities as serving some DM task. Consider, for example, *contact tracing* during the Covid-19 pandemic, that is, the task of monitoring and communicating with individuals who have been exposed to the virus. IS researchers looked at the effectiveness of contact tracing apps as contingent on their widespread adoption among the population (Trang et al., 2020). However, the extent to which such apps were effective from a public health perspective remains unclear. The question from an IS perspective could be whether they effectively supported "contact tracing" as a complex DM process; from a DT viewpoint, the question could be whether it ever morphed into a digital capability. In fact, contact-tracing, from a DM perspective, involved multiple stakeholders to collect data about contacts, informing the public about steps to be taken in case of exposure, monitoring and enforcing compliance with those steps (e.g., quarantine), and so on.

This shift of focus toward DM capabilities could leverage the existing case-based scholarship in DM, but such evaluations are more straightforward to conduct if the DM capabilities that the initiatives support were explicitly theorized. This includes, for example, being explicit about organizations and stakeholders involved or affected by the capability and the effect of such initiatives on their organizational structures and processes, as well as a clear conceptualization of the sort of *value* the initiative delivers.

Co-creating and shared use of digital resources

Digital technology creates new opportunities to engage local communities in supporting DM capabilities. Mobile technology, in particular, provides responder organizations with opportunities for social sensing, that is, leveraging communities as networks of human sensors. Unlike in traditional physical networks of sensors (e.g., smart river gauges), social sensing may rely on weakly structured systems in which technology is adapted to support sensing capabilities, rather than purposefully designed for that purpose. Future research could study the potential of social sensing initiatives to produce digital resources and assess their value by focusing on differences in outcomes when digital resources are generated through dedicated channels as opposed to adapted ones.

Furthermore, effective collaboration of DM professionals with communities poses challenges—it requires integrating different stakeholders in designing, developing, or supporting an initiative, as well as clearly communicate processes and tasks that are required by the initiative. Thus, it is important to study the value that co-creation and stronger collaboration between DM professionals and communities (e.g., to support DM tasks such as risk assessments) bring, for example, by increasing community resilience. Here, research may also focus on studying the cocreation of digital initiatives based on user centric designs and including stakeholders from DM professionals and communities.

Development of micro-capabilities

With respect to the involvement of digital volunteers, crowdsourcing—a supporting capability—can assist with a range of DM tasks. For instance, digital volunteers have been shown to perform tasks such as data labeling effectively within ML initiatives, which are limited in scope; we refer to them as "micro-capabilities." Key questions for incorporating the crowd in co-creation of digital resource pertain to assessing the sorts of tasks in DM that are suitable to be effectively crowdsourced—based on size and complexity of an initiative, for instance—as well as ways to ensure the quality and accuracy of crowdsourced tasks.

Future research could focus on developing strategies for creating and integrating micro-capabilities in DM processes. A first step in this direction is to study which existing capabilities can be supported by micro-tasking. This involves exploring interoperability, data exchange, and seamless integration between micro-tasking platforms and other DM tools and technologies, as well as training micro-taskers in DM-specific skills, including developing training modules, providing educational resources, and assessing the effectiveness of different training methods.

Entities undergoing transformation

Organizational change

As we discussed earlier, we found no clear indication that digital initiatives lead to organizational transformation. In the DM context, this may suggest that DT occurs through incremental steps, perhaps a marked series of initiatives that are progressively rolled out and integrated within organizations. The cumulative effect of these initiatives may eventually digitally transform a responder organization, leading to a redefinition of organizational identity and value proposition. Research in this area should focus on the effects of digital initiatives on responder organizational structures, processes, and identity. Studies could also focus on understanding the enabling conditions for successfully executing digital initiatives and how implementation (especially of highly successful ones) may precipitate organizational changes. Studies could focus on highly innovative responder organizations.

Self-organization

Public-driven initiatives revolving around self-organization show how communities coordinate and adapt to respond to disasters. Some of these initiatives evolve beyond their initial goals, maturing into self-organized communities that remain active not only to address long-term recovery needs, but also to engage in new disaster responses. The mechanisms through which such initiatives mature into more stable organizational structures remain unexplored. Understanding how to sustain public-driven initiatives beyond a specific disaster becomes crucial for supporting digital initiatives in the long term and delivering enduring societal benefits. Ushahidi, for example, went through such a transition by redefining its identity and value proposition; for many other public initiatives, however, the resources mobilized while self-organizing were eventually dispersed once the immediate disaster recovery concluded. Hence, research could focus on understanding the mechanism of how digital initiatives can change organizational structures as well as the changes of organizational identity as public initiatives mature into more long-term, sustainable organizations.

Value and challenges of technology-related initiatives

Creating public value through digital public resources

In DM, digital public resources emerge as pivotal for the efficacy of DM initiatives and, more broadly, for public good. Digital *public* resources are digital resources (i.e., encapsulating objects of value, modular, and programmatically accessible) that are made available for the collective benefit of all DM stakeholders, rather than for profit or competitive advantage. This is where crowdsourcing is key, as the creation of these resources, such as data repositories, ML models, and so on, involves harnessing collective knowledge to perform tasks of varying degrees of complexity, such as data entry, data annotation, programming, and others. Public resources, and the ability to leverage or create them through crowdsourcing, are almost indispensable in regions where the professional DM infrastructure is underdeveloped and local authorities struggle to generate digital resources independently. In those contexts, platforms such as Ushahidi exemplify how digital resources—in this case software—fill gap in regions where DM functions are inadequately equipped to leverage technology. Notwithstanding their potential, there is limited research that defines and explains how to leverage digital public resources effectively. This gap highlights the need for scholarly focus on the mechanisms for creating and leveraging public resources.

Another question concerns how to develop *global* digital DM resources that may increase the resilience of communities worldwide. Intuitively, such global resources could be modeled after prior successful digital initiatives. Their value, programmability, and modularity could, however, be studied as relative concepts that may be generalizable to different degrees across geographical, disaster-specific, or organizational contexts. For instance, the “value” of machine-learning models as digital resources for forecasting and early warning might significantly diminish in data-poor, disaster-rich regions. DT research in such regions may identify unique ways to foster DM capabilities through digital initiatives, such as transfer learning, an ML technique that leverages historical data from data-rich regions to make predictions in regions with scarce data.

Privacy and ethical concerns

Unique contextual elements in DM warrant studying privacy in the context of disasters. Users may be more prone to share personal information if it would help them cope with life-threatening situations. Even from a regulatory standpoint, agencies such as FEMA are allowed—under extreme circumstances—to collect, store, and redistribute personal identifiable information collected from public sources such as social media.[7] But scholars may even look at “violations” beyond unlawful sharing of sensitive information to include violations of users’ expectations regarding appropriate flow of personal information.

Disasters can increase technology users’ vulnerability to privacy violations. Two attributes of digital resources—modularity and programmatic access—intrinsically complicate controlling flows of personal data and put digital resources at higher risk, leading to privacy violations. For example, Sanfilippo et al. (2020) note that alert apps rely on third-party libraries, services of infrastructures, for advertising, analytics, performance monitoring, and so on. Their analysis of 15 apps showed connection to 142 third-party recipients. In other words, users who agree to share personal data with an emergency app may also be sharing it unwittingly with dozens of connected services and be unaware of this exposure and risk their personal data face. In 2017, for example, FEMA accidentally shared sensitive and identifiable personal information (e.g., users’ home addresses and their financial institutions) of 2.5 million individuals with a contractor supporting the Transitional Sheltering Assistance program, although the information was unrelated to contract fulfillment.

Ethics-by-design involves developing design principles and guidelines for software that will, in turn, follow ethical rules and support users in doing the same (e.g., Eismann et al., 2021; Nussbaumer et al., 2021). Following this idea, for instance, an approach was proposed to build ethical principles into a decision support system for DM by translating ethical dimensions (e.g., respect for human agency, fairness, transparency) into functional and non-functional software requirements (Nussbaumer et al., 2021). Ethics-by-design approaches rely on practitioner feedback and the involvement of technical and ethics experts. Future research could explore the integration of ethics-by-design within the combinatorial nature of digital ecosystems. The recombination of ethical-by-design resources with resources that have not been developed with ethical principles in mind may elevate the ethical considerations of the entire ecosystem or, alternatively, dilute the ethical integrity of an ethical-by-design resource in its ecosystem. This offers a rich area for investigation of how ethical standards can be generated, maintained, and propagated through digital resources.

Developing secure “digital resources” for information sharing

Modularity and programmatic access, two key properties of digital resources, may also heighten challenges related to information sharing, data ownership and privacy, trust and so on. This, in turn, may create resistance to digital initiatives. Research has suggested that such resistance may be overcome by trust in specific technologies. For example, a study of the potential to use blockchain technology in the humanitarian aid supply chain claimed that it helps overcome interorganizational barriers due to inherent features such as trust, immutability, security, transparency, and traceability (Ozdemir et al., 2021). Future research could explore sources of resistance to creating digital resources, such as those related to security, and how they can be overcome.

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[7] https://www.dhs.gov/publication/dhsfemapia-041-operational-use-publicly-available-social-media-situational-awareness (accessed May 28, 2024).

Infrastructural resilience and resilient design of digital resources

Digital initiatives rely on the "digital information infrastructure" (Piccoli et al., 2022, p. 2297) (e.g., communication networks, public cloud services). Disruption of such infrastructure may impede deployment of digital resources and capabilities, thereby affecting the effectiveness of digital initiatives. Instability and vulnerability of the infrastructure are environmental stressors peculiar to DM, and hence are crucial to consider in research.

Resilience should be understood in two ways. The first concerns how to design digital information infrastructures that minimize vulnerability to environmental shocks and guarantee continued deployment of digital resources during disasters. For organizations, this includes IT disaster recovery and business continuity planning by assessing infrastructural vulnerabilities and planning how to maintain uninterrupted access to digital resources during disasters. The second is *resilient design*, which requires studying design characteristics of digital resources to make them inherently resilient. This involves designing resources that operate with minimal infrastructural requirements. "Resilient" digital resources are also more suited to be effective deployment in regions with less-developed technological infrastructures. Resilient design supports more inclusive design of digital resources, so they can be deployed, operate, and support DM even in developing regions.

Limitations

We began this literature review to identify instances of DT in DM, relying on the current understanding of what constitutes DT: fundamental changes in the value creation processes (Vial, 2019) and transformation in "digital-first" organizations. DT was identified based on our subjective assessment of the impact of digital initiatives on organizational structures. We necessarily found ourselves applying these concepts to analyze research articles that were not purposely written to discuss the presence or lack of the constituent properties of DT and the enabling ecosystems. Most of the articles did not explicitly focus on DT or prioritize achieving conceptual clarity around what DT means; instead, they loosely focused on using technology in DM. One immediate problem is that while some IT-enabled initiatives we analyzed could potentially morph into digital ones, information hinting at such a possibility tended to be omitted, potentially leading us to underestimate the prevalence of DT in DM. Nonetheless, distinguishing between IT-enabled and digital initiatives prompts reflecting on the benefits of morphing IT-enabled initiatives into digital ones, and the potential benefits of pursuing programmatic accessibility, modularization, and servitization in the development of IT resources in DM, which is a precondition to study DT.

Finally, we only included in our sample those papers that met our quality criteria to focus on scholarship at the intersection of IS and DM. Future research could assess the maturity of digital or IT-enabled initiatives by restricting the focus to specific technologies and types of disasters while expanding the range of journals considered.

Conclusion

DT in DM is not solely the result of the use of new technologies or the implementation of new systems, but is also the accumulation of small digital changes that support all kinds of DM activities. These small changes may become a long-term process of innovation that builds upon previous digital advancements. The implementation of new tools, processes, and strategies may not be perceived as significant in their own right or at the time they occur, but collectively can lead to significant transformations in how DM stakeholders operate. This perspective stresses the need for continuous innovation and for researchers to search for novel ways to support the development and implementation of digital initiatives in DM. In this respect, elements to look for include the allocation of appropriate resources (e.g., government grants), the implementation of relevant technology, and the establishment of policies and procedures to govern the DT process. By recognizing the importance of these organizational efforts in DT, researchers and practitioners can more effectively identify the early signs of DT as an emerging process, rather than recognizing it only *ex post*.

CRediT authorship contribution statement

Diana Fischer-Preßler: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dario Bonaretti:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Deborah Bunker:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsis.2024.101865.

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