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Disaster management, crowdsourced R&D and probabilistic innovation theory: Toward real time disaster response capability

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**Abstract**

General agreement exists effective disaster management faces constraints related to knowledge sharing and a need for real-time research responses. Extreme case examples of disasters especially vulnerable to these challenges are global pandemics, or disease outbreaks, in which data required for research response are only available after the start of an outbreak. This paper argues the developing field of probabilistic innovation (innovation increasing probability of solving societal problems through radically increasing coordination of volumes of problem-solving inputs and analysis), and its methodologies, such as those drawing from crowdsourced R&D and social media, may offer useful insights into enabling real time research capabilities, with important implications for disaster and crisis management. Three paradigms of disaster research are differentiated, as literature is related to theory offered by post normal science, Kuhnian ‘normal science’ and Lakatosian ‘structural science,’ and the goal of achieving real time research problem solving capacity in disaster crisis situations. Global collaborative innovation platforms and large-scale investments in emerging crowdsourced R&D and social media technologies together with synthesis of appropriate theory may contribute to improved real time disaster response and resilience across contexts, particularly in instances where data required to manage response is only available after disasters unfold.

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1. Introduction

The emergence of social media and other recent technological advances has enabled crowd-sourcing [30] to effectively support disaster management efforts, as documented globally, for example, in New York (Hurricane Sandy), the Philippines, Japan [51] and Haiti [59]. Crowd-sourcing can provide important support for decision making [55], including under time pressures associated with crises. Crowd-sourcing and expert-sourcing can be effective in managing community engagements and interactions [58], particularly under uncertain conditions. This paper argues the advent of crowd-sourcing and social media technology may support a new era in knowledge management, offering important advances in the development of disaster management theory, and extends theory relating to post normal science [22], Kuhn's notions of 'normal' science [34] and Lakatos's consideration of theoretical resistance to change [35] to provide new perspectives of theory development in disaster risk reduction.

Central to the need for new theory development and frameworks is the problem-disruptive potential of social media and its enablement of crowd-sourcing. The rise of crowd-sourcing [30], defined here as sourcing inputs or resources from the 'crowd' or from an open call to the public, potentially heralds a new paradigm in problem solving; as problem solving data inputs can now be obtained from the general population, or the crowd, on a scale hitherto unimaginined. Crowdsourced research and development (R&D) relates specifically to crowd-sourcing which seeks to source information for problem solving research purposes, and expert-sourcing is crowd-sourcing for inputs from experts, a form of crowdsourced R&D. Crowdfunding is crowd-sourcing applied to raise funding. A new stream of literature with a focus on real time problem solving, namely 'probabilistic innovation' [10] suggests that by exponentially increasing volumes of problem solving research inputs (expert and non-expert) from millions (in the 'crowd'), radical acceleration of medical research can be enabled, and research yield timelines can be 'crashed,' thus radically accelerating the pace of scientific research. This developing stream of literature, extended to disaster management, arguably offers useful insights for those seeking to build theory around increasing effectiveness of real time crisis management.

If what took medical researchers years to achieve could be produced in real time, this would amount to a process revolution in medical science. The field of disaster management may be an important ‘development ground’ for important research into how real time capacity can be attained, and the application of real time...
probabilistic innovation in the form of crowdsourced R&D [10] to crisis disasters is therefore crucially important. A useful heuristic, then, is the example of such a disaster in the form of a disease outbreak, or pandemic, in which the data needed for research to solve this problem are only available after the start of the outbreak. Disaster management is therefore taken to be an important context for research into how to develop probabilistic innovation theory for the following reasons.

First, probabilistic innovation, in the form of crowdsourced R&D may hold important promise, as the probability of solving problems can be increased exponentially as the volume of inputs is increased exponentially. A core assumption underlying this notion, however, is that exponential increases in crowd inputs can transmit to useful outputs [10]. Given effectiveness of probabilistic innovation hinges on this assumption, knowledge of how to operationalise probabilistic innovation is however lacking, and research has a long way to go before radical acceleration of time scales in ‘conventional’ medical research (such as research into cancer, diabetes or ageing) becomes a reality. Hence, the extreme conditions of disasters can provide a useful testing ground for theory relating crowdsourced R&D and social media technologies contributions to data collection, integration and analysis, as the potential value contributions of probabilistic innovation are more immediately evident and clear under disaster conditions. Process innovations associated with probabilistic innovation are taken to derive from management theory generally, and knowledge management theory more specifically.

Second, present global threats to human health in the form of potential global pandemics, including Ebola (WHO, 2015), Middle East Respiratory Syndrome (MERS-CoV) [17], and viruses which cross-over from animal species to humans, such as swine flu, or H1N1 [38], require urgent attention from researchers. Given the potential loss of life and consequences of a lack of knowledge relating to how to enable real-time disaster management research, not undertaking this and similar research into probabilistic innovation would arguably be problematic. If the probabilistic innovation methodology offers some degree of probabilistic improvement in knowledge creation under disease outbreaks (or disaster management in general), then this may be an important developing area of study, or field, deserving of scholarly attention.

Third, given the lack of significant progress in certain biomedical research [41,9,10,24], and despite increasingly radical innovations in scientific fields [27], in the context of a global outbreak of chronic diseases such as diabetes, HIV and a host of other conditions borne by both ageing populations as well as those in impoverished economies, it is argued that these problems constitute a disaster in itself, and that the development of probabilistic innovation ideas as a stream of literature and research methodology may hold much promise to accelerate research to solve these societal problems, in that it makes attainment of real-time knowledge problem solving capacity an exclusive focus of theory development.

Having outlined a justification of the importance its research problem, the paper proceeds as follows. First, disaster management literature is reviewed, in order to demonstrate the rapidly increasing use of social media in disaster management contexts, and to justify arguments placing crowd-sourcing and ‘open sourced’ knowledge inputs at the heart of a paradigm shift toward open innovation in disaster crisis management. Next, having laid groundwork for a justification of arguments made, a model is derived, which seeks to offer a classification of disaster literature according to three paradigms corresponding to types of science, termed ‘post normal’ science [22], Kuhnian ‘normal’ science [34] and Lakatosian [35] ‘structural’ science. ‘Linking disaster literature to a focus on real time problem solving and research capability and to these three bodies of theory, this paper seeks to enable further theory building to better contribute to disaster problem solving and research. Disaster management literature is now considered.

2. Disaster management and the probabilistic innovation paradigm

According to Alexander [1], “the widespread adoption and use of social media by members of the public throughout the world heralds a new age in which it is imperative that emergency managers adapt their working practices to the challenge and potential of this development.” It is argued here emergent technologies have enabled advances in social media and crowd-sourcing, which have in turn enabled radical new potential for knowledge and data collection and analysis, particularly in real time disaster situations. Realising the full potential of this new age, and harnessing the full potential of capabilities enabled by emergent technologies, however, remains a challenge. Underlying the rise of social media and crowd-sourcing are perhaps mechanisms and causal channels through which knowledge management efficiencies offered by these new technologies can contribute to more effective disaster management, and real time problem solving capability. Which might ultimately feed into problem solving system theory development in other contexts.

Arguably, this potential can be described as ‘probabilistic’ as exponential increases in problem solving outcomes are possible [10,11]. However, literature seems lacking in explicit focus on theory development in support of potentially exponential increases in problem solving in real time. Probabilistic innovation, is therefore taken here as a stream of literature explicitly seeking to focus on theory development around harnessing potential of social media and crowd-sourcing in support of real time research problem solving, particularly in disaster contexts were data required to manage response is only available after disasters unfold.

This stream of literature, as well as appropriate methodologies in support of this end, is grounded in emerging theory related to citizen science, or the participation of expert and non-expert ‘citizens’ in scientific research [4], participant-led research [54] and principles of post-normal science [22] seeking verification of science through maximised transparency and engagement of stakeholders. Arguably, these theoretical frameworks have important implications for disaster management, and probabilistic innovation seeks to focus theory development explicitly on real time problem solving, applied to disaster management, particularly in terms of crisis management under time constraint [11].

Certain other theoretical frameworks also offer useful insights for disaster management, and constraints to real time problem solving. O’Sullivan et al. ([43]:238) stress recent disasters, such as “the oil spill in the Gulf, the tsunami and nuclear reactor leak in Japan, global pandemic, and the earthquake in Haiti all demonstrated the complexity of responding to events which have cross jurisdictional, organisational and other forms of boundaries.” However, at the heart of crisis response is the knowledge aggregation problem [28,56] relating to the need to bring tacit knowledge inputs together across geographical and other boundaries and barriers at a single point in time; complexity an inherent characteristic of this process.

Core tenets of complexity theory such as emergence, self-organisation, non-linearity, adaptiveness and connectivity offer useful insights into the management of disasters. Taking complexity theory as a reference frame for disaster management (DM) is useful as it provides insights into interactions between system components and systems and their larger environments; particularly over the course of a disaster, as constituent phases have different objectives and unique complexity [43]. Specific disasters are the “product of complex conditions, in both the environmental
and social realms and response dependent on complex interactions of institutional response and environmental conditions [25]. Closely related to complexity theory applied to disaster management is the need to manage information and knowledge in contexts of extreme complexity, and the need to understand causal mechanisms and channels as well as to develop theory that guides the management of knowledge inputs under extreme conditions.

In the wake of the 2009 influenza A pandemic as well as the 2003 Severe Acute Respiratory Syndrome (SARS), the recovery and planning phase of the DM process has been ongoing, well after these outbreaks; but critical across phases is knowledge of soft capital (such as people and knowledge) and the dynamics of critical social infrastructure and how community capacity is facilitated through social infrastructure such as “communication networks, social capital, collaboration and community engagement, and methods for evaluating resilience-oriented interventions” [43]. Statistical models have been used to model risk and variability, for example in cases of tornado risk [47], reflecting an increasing trend toward modelling information in crisis response. This process of modelling different dimensions of crisis and response, however, is dependent on both volume and quality of data collection and analysis. Mapping of hard and soft system infrastructure, at both the micro and macro levels, and developing models of these relationships is important, yet has typically been under-researched [43]. Frameworks need to be developed that are sufficiently robust to crisis situations, but that can maximise real time data collection and analysis.

Study of disasters reveals development of resilience abilities in populations facing disasters; such behaviours can be explained using applications of emergent system behaviour and Complex Adaptive Systems Theory which seeks to understand emergence within adaptive systems [14]. O’Sullivan et al. [43] offer a framework for critical social infrastructure related to health and disaster resilience, which models culture and dynamic networks as impacting formal and informal structures, protocols, information and people-related aspects, which are considered micro-level inputs, and their influence on macro-level outputs such as connectedness and collaboration in relation to dynamic contexts, or states, situational awareness and adaptive response. Such frameworks highlight the importance of emergent responses to crises, which can also result in real time problem solving theory development.

Central to O’Sullivan ([43]: 246) model is the reconceptualization of the management of disasters from risk management to resilience, the latter inextricably related to dynamic and changing complexities, necessitating a change away from command and control DM models toward collaboration, as intervention designs need to emerge from the complexity of a specific situation, “tailored to the community context at any point in time” Arguably, shifting from command and control toward collaboration and stakeholder engagement reflects the emergence of social media and open systems of knowledge and information sourcing, or crowd-sourcing, as well as a new age in community and population involvement in data collection and analysis [22,4,54].

Crowd-sourcing (“a model that uses the general public, or the crowd, for the purpose of utilising skills, talents, or observations as sources of knowledge and expertise”) can provide real-time data, enabling quick response to disasters [51]. When New York faced the disaster wreaked by Hurricane Sandy, Instagram users spontaneously formed a participatory network, sharing images of the destruction, all the while Twitter feeds helped to coordinate assistance, and mobile truck deliveries of food were made possible as drivers micro-blogged their locations via geotagged information; hybrid alliances between online platforms and offline locations developed as interactive crisis maps with links to Facebook, Twitter or email emerged, allowing Red Cross, municipal and other agencies to provide real-time updates [51].

Social media can enable more efficient crisis response through enabling cross-platform accessibility and constant information flows in the form of just-in-time information [1], and together with advances in event monitoring in emergency scenarios [20] can offer new potentials for real time disaster response. According to Tierney [51], the “proliferation of mobile devices and applications coupled with the ease and speed of online dissemination...has permanently changed the way we understand and respond to events around us” and as a result, “crowd-sourcing and other online participatory practices are becoming increasingly important to emergency personnel,” providing faster localised information in disaster situations. The use of open innovation platforms of knowledge sourcing such as crowd-sourcing, supported by recent technological advances, offers further probabilistic advantages; when exponential increases in volumes of inputs are enabled, more complete information and knowledge on problems is obtained, and problem solving can be accelerated. These advances provide a systemic infrastructure that may support high volumes of expert and non-expert inputs into many different problem solving processes based on knowledge of disaster crisis maps.

Information provided by disaster crisis maps include knowledge of power outages, shop availability, fuel availability and medical services provided by neighbourhood residents; similar dramatic and spontaneous citizen responses to disasters have been documented across the world, for example in countries such as Chile, the Philippines, Japan and Haiti [51]. Platforms were typically created for Short Message Service (SMS) and Twitter information to automatically be geotagged with longitude and latitude coordinates and integrated into a centralised map that uses public inspection and verification; this process allows crowd-sourcing to underpin disaster recovery efforts, even under conditions where voice communication is down [51]. What is particularly salient here is the use of citizen users and the use of crowd-vetting of information. This may reflect the shift to a new paradigm of potential exponential increases in knowledge and information inputs from the crowd [10], as well as the use of the crowd to vet or filter useful information [1]. Another indicator of the rapid emergence of these processes is the rise of non-profit crowd-sourcing platforms to support disaster management.

Ushahidi is a non-profit software firm crowd-sourcing platform developing free general public licence software for information collection, visualisation and interactive mapping which was used in the Haiti earthquake disaster; as part of this process, Twitter ‘classifiers’ have been developed, algorithms which identify important tweets in real time, automatically organising disaster information [51]. Free open source systems can support non-profit platforms. Server-based disaster management software, such as the free open source Sahana Disaster Management System are supported by a host of proprietary systems; these systems, however, tend to operate in silos, or in functional areas, and social media offers the advantage of knowledge sharing across these boundaries [59]. Similarly, the non-profit Innovative Support to Emergencies, Diseases, and Disasters (InSTEDD) develops free open source platforms to support collaboration and disaster information flow across geographical, cultural and organisational boundaries [51].

Collective coding groups (for example Civic Hacking and Code for America (CfA)) use volunteer developers for partnerships with stakeholders such as municipalities and entrepreneurs; privacy, security and regulatory barriers can be transcended as crowd-sourcing which uses these processes can address both open data and security issues [51]. There is thus evidence of the development of probabilistic innovation applications across the disaster management spectrum. What is lacking, however, from the literature is a clear synthesis of this literature and advocacy supporting the
development of an ‘umbrella’ field for this literature. It is hoped that probabilistic innovation provides a useful description of what is considered here to represent a fundamental paradigmatic shift toward the democratisation of science [22,4,54] and the way information and knowledge is used to support disasters and crises, with important implications for human wellbeing.

The use of a probabilistic approach to disaster management is not unprecedented. Tseng and Chen [53] propose a probabilistic approach to disaster management, in terms of planning. Potential direct and indirect simulated losses caused by disasters can be modelled, generating exceeding probability curves, and risk control arrangements can be modelled probabilistically [53]. It is argued here that the extension of probabilistic logics to information and knowledge sourcing is a natural extension of these literatures. The development and application of a probabilistic innovation theoretical framework to disaster management may be particularly important due to the sheer diversity of disaster contexts, and the need for disaster management cycles to source and incorporate information and knowledge in a way that is robust to uncertainty and the unique circumstances associated with each disaster.

3. Categorisations of disaster literature

Attainment of real time research or knowledge creation capability is the goal of probabilistic innovation [10], through the use of different methods to accelerate the rate at which information and knowledge can be managed in support of problem solving. Effectiveness of attempts to facilitate real time problem solving is, however, expected to differ according to types of disaster.

A disaster management cycle consists of a continuum of interlinked activities, including processes associated with impact, response, recovery, development, prevention, mitigation and preparedness [13]. Traditional disasters, such as natural phenomena (for example, earthquakes, cyclones, volcanic eruptions, tsunamis, wildfires, floods, landslides and drought) pose increased risk as growing populations in disaster-prone areas require more water and sanitation; greater use of tin roofing, for instance, is problematic in cyclone-prone countries as disasters can make building materials dangerous to populations [13]. Disasters can also differ by threat level, and by estimates of probable maximum loss [7].

Positive externalities also result from international collaborations around disaster management which seek to reduce direct loss of national assets and the diversion of national resources away from development; such efforts, however, need to balance prevention, mitigation, preparedness, response, recovery and disaster-related development [13]. Disaster risk, however, has also been exacerbated by the development of ever-more intensive transport systems, more airline traffic, increasing population levels (particularly in natural disaster-prone areas), as well as increasing transport, use, and disposal of hazardous materials, including nuclear materials [13]. The increasing vulnerability of populations to disasters highlights the need for adequate real time research responses, given that the data needed for this life-saving research response is in many instances only available after the start of the disaster.

This work seeks to offer a categorisation of disaster literature, in an attempt to provide a useful perspective of how scientific research and insights related to three ‘paradigms’ of disaster or problem responsiveness can help future theory development focusing on real time response to disasters. Discussions in following sections seek to build on this notion of responsiveness, and its differentiation, with a special focus on real time disaster management capability, the primary focus of this article. Effectively this research seeks to differentiate real time disaster response literature, and link related literature in support of a focus on real time response.

A crowdsourced system, using crowdsourced R&D, developed according to the principles of probabilistic innovation, may offer a useful platform for addressing the real time constraints of disaster management, if it can source data and information on a sufficiently wide scale in real time, in a way that offers quality control of inputs for decision making and as research inputs into real time research (offering decision-makers problem solving capability based on relatively high volumes of inputs). The challenge, however, is to understand how this might be done; insights into Internet-based collaboration technologies may offer a useful perspective in this regard.

3.1. Internet-based collaboration technologies

Certain work to date has sought to develop frameworks for the application of crowd-sourcing in firms to support management decision making [55]. This body of literature offers firm-level insights which might be applied to disaster contexts. Woolley et al. [58] offer insights for how firms or organisations can structure interactions and manage community engagements by leveraging Internet-based collaboration technologies (CT), such as crowdsourcing and expertsourcing. The development of collaborative web-based geographic information systems frameworks [3] and other Internet-based collaboration technologies can now leverage social interactions on online platforms, and between members of online communities as well as firms; an example is the use of crowd-sourcing to source t-shirt artwork using contest formats with monetary rewards in addition to crowd engagement at different stages (such as ideation, development and launch) of the innovation process [58]. Event monitoring technologies [20] can also be merged with Internet technologies to facilitate real time disaster response and problem solving. Collaboration technologies can provide important infrastructure to support real time response, but also longer term disaster response. However, real time response payoffs can be substantial, as disaster consequences met with adequate immediate response can maximise effectiveness of response.

However, certain conditions are more conducive to CT value creation and capture using co-innovation, such as when (i) expert-based communities are developed rather than open crowds, (ii) repeated long-term engagement is used to develop communities, (iii) iterative content development mechanisms are used among and between community members and firms, (iv) task or problem evolution is facilitated during engagement, (v) expert community members are engaged in content management, and (vi) time durations of community engagement with tasks or problems are constrained [58]. Under certain conditions crowdsourcing and expertsourcing for R&D, termed crowdsourced R&D here, can leverage Internet-based Collaboration Technologies in support of accelerating knowledge management and production in real time.

3.2. Crowd-sourcing platforms and value of crowd-sourcing in other contexts

Effective disaster management can have important results. Such efforts can contribute to lessening inequality across nations. Global political, economic and social stability is contingent on “bridging the gap between developing and developed nations” and mitigating and containing the effects of disaster is therefore critically important [13]. Advances in disaster management offer encouragement. Examples are rapid vaccine development in the wake of the 2009 H1N1 influenza pandemic [19], and the unprecedented scale of global collaboration associated with the HIV/AIDS pandemic [46]. Given global payoffs from disaster management efforts, investments in global collaborative
networks, or platforms may offer important contributions to disaster management, and ultimately to the development of real time research response capability. Emergent social media capabilities support more advanced uses of crowd-sourcing, the uses of which might not yet be fully explored.

The potential value of the crowd-sourcing literature for disaster management is in the way useful insights can be gained from drawing problem solving information inputs from large numbers of people, or the ‘crowd.’ According to Tierney [51], crowd-sourcing can contribute to emergency assessment through (i) citizen development of software platforms to capture voluntary information, and (ii) crisis mapping, both which can incorporate crowd-vetting of information. However, it can also facilitate other forms of data collection, synthesis and analysis. Given arguments made, to provide a more complete perspective of crowd-sourcing’s potential for information collection and analysis, literature relating to historical and contemporary applications is considered as follows.

The use of the general population (the crowd) to solve research problems is not new. The Longitude Prize (1714) solving the navigation problem of ships and Alkali Prize (1783) for separation of salt from alkali are examples [6], but it is rapid advancement in information technology that has created new opportunities, particularly Web 2.0 technologies and social network capabilities offering cost, time and location advantages for problem solving. Disaster risk reduction theory and practice can benefit from ongoing theory development around these capabilities.

Proof of concept for crowdsourced scientific research effectiveness and time savings has been demonstrated; Innocentive, for example, an internet-based platform soliciting problem solving input from scientists [2,5,6] as an 85% success rate at solving its premium challenges, offering solvers from $5000 to $1 million depending on complexity and nature of challenges [31]. Such crowd-sourcing platforms offer disaster risk reduction research a useful option under time and cost constraints (solvers are only paid for solutions). Other crowd-sourcing models also offer evidence of similar success, including ‘crowdSPRING’ (graphical and industrial designs), ‘ChallengePost’ (government services problem solving), ‘Chaoidx’ (corporate market research), ‘VWorker’ (virtual technology workers can bid on projects), and ‘IdeaScale’ (idea development) [6].

Disaster management projects can also take advantage of useful ways in which work can be broken up and performed using crowdsourced methods, examples of this include Amazon’s Mechanical Turk (micro tasks requiring human skills), TopCoder (programming, design and development), Guru.com (skill-based talent search), eLance (graphic design, programming and web development), LiveOps (call centre services), oDesk (services), CastingWords (transcription), Crowdflower (verifying information and categorising images), and Samasource (distributing computer work to disadvantaged regions) [37].

Crowd-sourcing can also be useful at the interface between social media, in disaster contexts, and can offer ‘early-warning’ systems for disease, or bio-surveillance [15]. NASA is involved in a project to develop crowdsourced software solutions to detect asteroids or near-earth objects in the form of the Asteroid Grand Challenge [42]. Distributed computing enlists home users in collection and processing of radio signals from space, and Folding@Home uses 160,000 home computers to analyse protein folding applied to neurodegenerative diseases and cancer research [52]. Cancer research UK (CRUK) has enlisted to crowd-sourcing to identify cancer cells through citizen science [52]. These techniques are also useful to search abandoned compounds for new applications, and in clinical trials [52]. These have disaster management applications, offering useful mechanisms for data to be collected and analysed more quickly and effectively than conventional research systems.

Organisations offering digital humanitarian services include MicroMappers (combining crowd-sourcing with machine learning), Standby Task Force (organising digital volunteers into networks, offering interface for 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) [16]. Probabilistic innovation can be taken to be an umbrella category of a stream of literature which seek to draw together crowd-sourcing literature, social media literature and other streams of literature which primarily relate to the real time response category of disaster response, as what is lacking is theory which can make explicit the causal mechanisms and channels through which emergent technologies and capabilities can be better harnessed in support of real time crisis response and research problem solving. Arguably, we have entered a ‘new age’, and what remains to better develop categorisations and theoretical frameworks to more specifically focus linkages between these developments and attainment of real time response.

Arguably, if a real time research methodology based on a synthesis of crowd-sourcing and developing social media applications could be developed to address disasters, then it could be applied to other, more longstanding problems. The development of these methodologies might usefully be undertaken under disaster conditions, closely related to the use of knowledge management systems and processes. Having considered examples of crowd-sourcing and its potentialities relevant to real time problem solving, the role of social media is now revisited.

3.3. The contribution of social media to knowledge management systems and disaster management

The international disaster management response to the 2010 Haiti earthquake was a complex undertaking relying on extensive use of knowledge management systems (KMS), as US agencies used social media technologies (such as wikis and collaborative workspaces) as core knowledge sharing mechanisms [59]. Digital humanitarianism is an example of a movement employing advanced technologies and social media to accelerate major disaster relief efforts, such as in the case of the Nepal earthquake, as crowd-sourcing, social media, aerial imagery and disaster mapping are used to find actionable data in post-disaster information [16].

In emergencies, social media are typically used in seven distinct ways, namely to (i) track public debate, (ii) monitor situations, (iii) extend emergency response and management, (iv) for crowd-sourcing and collaborative development, (v) to enable social cohesion, (vi) to support donations and causes, and (vii) to better enable research [1]. Social media tools can enable open online exchange of information through interaction, and manage conversation or interaction content (unlike typical Internet and communication technologies, or ICTs) as information artefacts, providing many contributions of small knowledge chunks in different forms, which are easy to acquire, share and use [59]. Tweets, hashtags, tagged images, and experiences of those involved are accumulated, which offers certain useful information, such as where the damage is most intense and more information, and volunteers provided crowd-sourced checking of tags and keywords for priority, a process particularly important in contexts where information overload is a dominant problem [16]. Social media therefore also supports ad-hoc network formation, linking people with different functions, expertise and contexts, as media becomes an artefact “around which knowledge is organised in clusters, such as comments on blog posts or tags on images” ([59]:7). Arguably, social media can contribute important and perhaps unique information management advantages in real time crisis situations.
Social media use can however also have potential for negative developments. Rumour dissemination, the undermining of authority and promotion of terrorist acts are examples, and ethics of social media use are important; however, social media are also a “robust means of exposing corruption and malpractice” and global adoption and use of social media by populations “heralds a new age” in which emergency managers need to adapt working practices to the challenges and potential of this new age ([1]:717). As previously indicated, the notion of a new age in science enabled by technology associated with involvement of populations in ethical scrutiny is key to theory related to the field of post normal science [22].

“Effectively maintained, social media eliminated linear, manually intensive knowledge sharing processes typical of past response efforts and permitted localised ‘crowd-sourcing’...of ideas from numerous experts simultaneously” but ineffectively managed social media can be abandoned, grow unwieldy and increase workloads “for already over-taxed responders” ([59]:8). Reviews of studies of social media in disasters suggests a focus on themes relating largely to (i) functioning of social networks and their use, and (ii) how this can be monitored or enhanced, as well as (iii) use in crises and interactions of social media with traditional information sources [1]. As stressed previously, event monitoring technologies [20] can be usefully combined with social media inputs for crisis information systems in support of real time response.

Arguably, further more specific research is urgently needed, into how high volumes of ideas and information sourced from the expert and non-expert crowd can be better managed to result in real-time research. Social media in disasters is therefore an important area from which useful insights into real time research capability can be derived. A useful analogy, perhaps, is that of an airport, which has a certain capacity for aircraft to take off and land. If this represents the amount of ideas that can be managed by the probabilistic innovation system, then the goal would be to increase these volumes exponentially; to ‘take off and land’ millions of ideas off a single platform. This might seem intuitively impossible, but given a radical innovation of the crowdsourced R&D platform, this might one day be possible. Knowledge of mechanisms through which social media operate to enhance (or constrain) crisis response is therefore important for further research in this area. The success of such a process could be applied generically, no matter how unique different disasters are.

Each disaster is unique, however, presenting “entirely new environmental, geographical, political, economical, and sociological concerns” and responders need to build new knowledge structures under compressed time horizons to capture information to be used later; common capabilities, however, underlie this process, such as transportation systems and systems of experts (such as medical and social workers) ([59]:7). Arguably, a real time probabilistic innovation system could ultimately add value as a generic platform applied to different disasters. Such a system, however, would require new thinking about how to transcend ‘silo’ based systems thinking.

Traditionally, information management models have applied centralisation as their guiding rationale, and responders have had to rely on information systems operating in silos which collect and reconcile information with existing organisational knowledge and present this knowledge to decision makers as an expert expertise; with responders working as teams following parallel processes [59]. In order to understand how theory can be developed to integrate crowdsourced R&D processes into disaster management models, it is necessary to look to more diverse theory for additional insights, and relevant to this is theory relating to boundary management of knowledge.

3.3.1. Frameworks and metamodels

According to Carlile [8] an irreconcilable tension exists between three different perspectives of boundaries, (i) an information processing perspective which understands knowledge as something to store and retrieve, (ii) an interpretive perspective which stresses the need for shared meaning as a basis for knowledge sharing, and (iii) a political perspective which highlights how different interests can impede knowledge sharing. In a global context of integrated disaster management logistics, and integration of work by civilian, government and military networks [50], as well as increasingly networked collaborations between institutional and individual stakeholders in disaster management, theory development with a focus on managing boundaries is perhaps of growing importance. Knowledge flows across different kinds of boundaries is an important area of future probabilistic innovation research. However, it is important not to lose sight of the emergence of a range of different sub-fields within the disaster literature, and provide a synthesis of these. Given the multidisciplinary nature of disaster research, a mapping these sub-fields is necessary. An example of such as field is disaster operations management.

Disaster operations are the set of activities undertaken to diminish the impact of a disaster; the stream of research associated with these activities has developed into the field of disaster operations management (DOM) [23]. Disaster management (DM) is the “management of the risks and consequences of a disaster” ([44]:218). Such risk can be modelled using probabilistic models of estimates of probable maximum loss [7]. Although disasters are unique and require their own management process, their impact can have common features and responses which are transferable; but key to disaster response is weighing the amount of information needed versus the time available when making decisions, and a common disaster management ‘language’ is necessary for this [44]. Such a DM language requires metadata, which is structured and maintained, and allows semantic descriptions of content and services in support of the resilient capabilities of organisations and communities in the face of disasters [44].

Othman and Beydoun [44] offer an example of a DM metamodel which seeks to incorporate modelling techniques into a comprehensive model of disaster response; with specific reference to the Christchurch New Zealand earthquake and the nuclear meltdown in Fukushima, Japan. Understanding the complexities of DM requires a recognition of the inter-dependencies between health care and “broader social systems and how they intersect to promote health and resilience before, during and after a crisis.” However, these models need to be extended to incorporate the consequences of response itself. An example of this is the way medicines used to treat pandemics can increase vulnerability to further pandemics.

The use of certain antivirals to treat seasonal influenza outbreaks has the potential to compromise the effectiveness of their use in the case of pandemics [or other pandemics] due to the ability of these strains to develop resistance; specifically, the use of M2 ion-channel inhibitors such as amantadine and rimantadine might be particularly problematic, according to the Centres of Disease Control [26]. In order to build global disaster models that incorporate these eventualities, it is necessary to pool resources, in much the same way as planning for global pandemics is done.

The Global Outbreak Alert and Response Network (GOARN) is a “technical collaboration of existing institutions and networks who pool human and technical resources for the rapid identification, confirmation and response to outbreaks of international importance”, providing “an operational framework to link this expertise and skill to keep the international community constantly alert to the threat of outbreaks and ready to respond” [57]. The need for global outbreak response networks is increasingly salient in a context of potential species crossovers. At the human-animal interface (HAI), influenza viruses such as avian virus subtypes
H5N1, and H9N2, and swine virus subtypes H1N1 and H3N2 have emerged, highlighting the potential threats of pandemics that arise from species crossovers [57]. The core thesis of this paper is that given the potential consequences of catastrophic disasters, there are consequences associated with not developing focus on disaster research theory and best practice drawing on the principles of probabilistic innovation. Arguably, the congestion, complexity and uncertainties of disaster knowledge management require high volume idea inputs to solve problems in addition to knowledge and information inputs, and developing the field of probabilistic innovation with a special focus on managing these inputs in a way akin to ‘high volume air traffic control’ might ultimately offer the hope of real time research problem solving. Radical acceleration of biomedical research and other social problem solving research, including climate change and other disaster management applications may be possible if crowdsourced R&D lives up to the promise suggested by probabilistic innovation theory.

3.4. The real time response paradigm

A synthesis of arguments made in this work is summarised in Fig. 1, which seeks to offer categorisations to clarify relationships between problem solving and temporal horizons in certain literature relevant to disaster management. In Fig. 1, problem solving in research is represented as occurring in three temporally defined paradigms. According to the first paradigm, namely the real time response paradigm, problems need to be solved in real time, as problems are time-critical. This paradigm is considered to potentially benefit from theory development related to post normal science theory [22], which seeks to spread the scientific validation process across populations, and work in the citizen science area [4] drawing also from participant-led research [54], which can offer principles useful for real time disaster management based on how populations can help not only to provide large-scale quality data in crises but also how they can contribute to analysis of data and problem solving in real time.

The real time response paradigm (the primary focus of this paper) relates to crisis management, or the crisis management aspect of disaster management. Knowledge in this paradigm is taken to essentially be probabilistic, or not certain, and to solve problems there are relatively few mechanisms available to those seeking to solve such problems other than to increase volumes of inputs and rely on probabilistic increases in probability of problem solving. This problem solving ‘space’ is inherently problematic, as ethical and practical challenges of social media [1] and crowdsourcing [10] need to be managed, while these new technologies are used to leverage radically increased data collection under time constraints.

Probabilistic innovation draws ontologically and epistemologically from literature suggesting emergent properties and mechanisms may be useful for real time research (and non-research) problem solving [11], such as insights offered by research into how evolution of successful candidate ideas occurs, such as genetic algorithms used to develop theory on adaptation based on mutation algorithms applied to computational protein engineering [39], which together with a host of other literatures stress the importance of understanding emergent forms of problem solving [21,40,32,33,48,49].

Probabilistic innovation is broadly named from this body of literature [11], which, as explained by Mitchell [39] essentially links emergent properties of problem solving to evolutionary theory, which understands evolution as “in effect, a method for searching among an enormous number of possibilities for ‘solutions’ whereby probabilistic innovation is perhaps an appropriate description of this process. This process naturally fits with real time disaster management, as in certain crises an enormous amount of data needs to be sourced, managed, and subjected to an integrated analysis in an instantaneous process. It is not the place here, however, to deepen discussions on ontological and epistemological characteristics of probabilistic innovation; the objective here is instead to offer a differentiation of categorisation of disaster theory and literature, in the hope future theory building can unite appropriate and useful streams of literature in support of real time problem solving (the real time response paradigm discussed here).

It is the problem space of real time disaster management which may hold answers for radical improvements in other paradigms of

![Fig. 1. Problem solving paradigms and importance of the real time response sciences as laboratories of scientific change.](image-url)
problem solving, as a ‘natural laboratory’ for crisis management and real-time problem solving capability. Mechanisms through which social media and crowd-sourcing can be used to disrupt knowledge constraints to problem solving are not limited to crisis management contexts however, but can also perhaps operate in the other two paradigms. Similarly, statistical and other model outcomes and problem solving platforms from the structural problem space [47] can also offer useful insights for real-time disaster response and problem solving. Event monitoring [20] and other technologies can be developed in resource response or structural paradigms for application in real-time response.

3.5. Resource response paradigm

The second temporal paradigm presented in Fig. 1, namely the resource response paradigm, relates to medium term research responses to crises or disasters, (where time as resource is less scarce, and resources are key to disaster recovery efforts) can be used to facilitate resource flows to problem sites. In the real-time response paradigm, time limitations are taken to essentially constrain the flow of resources and their effectiveness in support of problem solving, and it is maximised knowledge flows which might best contribute to real-time problem solving capacity to leverage what resources are available. Theory relating to this paradigm relevant to constraints to scientific advances might best be likened to conditions described in Kuhn’s [34] analysis of paradigms and resistance of scientists themselves to scientific progress, in that work is conducted within paradigms, and paradigms are not themselves questioned. The availability of time for problem solving in this paradigm reduces the pressures for emergent problem solving, and Kuhnian paradigm dynamics are not disrupted in problem solving processes in the same way as real-time research responses.

The resource response paradigm problem solving process is considered to be dependent on the efficiency and effectiveness of resource mobilisation and ability to source resources to manage consequences of disasters, but outcomes of this process at this stage are more quantifiable, and no longer as ‘probabilistic’ where outcomes are not certain but need to be estimated as probabilistic outcomes of estimation. Key to problem solving at the resource response stage is the ability to channel volumes of resources. However, it is argued here that the disruption of problems obtained through integration and analysis of high volumes of knowledge inputs based on social media and crowd-sourcing technologies, can also be applied to disrupt problems in the resource response paradigm, as crowdfunding and the engines of social media and crowd-sourcing as knowledge problem solving mechanisms can also change processes, and produce radical innovations, increasing efficiency and effectiveness of resource response.

3.6. The structural paradigm

The structural paradigm considered in Fig. 1 relates to the long-term structure of knowledge problem solving in science which underpins disaster management. However, the structural paradigm is considered to represent the ‘long-term’ and perhaps less responsive body of scientific research, drawing from Lakatos’s [35] notion of theoretical fields which resist evidence counter to their core theoretical assumptions. What perhaps characterises this paradigm is lack of breakthroughs, or failure to solve longstanding problems. Failure to solve chronic disease, problems such as Zika or drug-resistant tuberculosis are examples from pharmaceutical research, but other societally important problems (for example climate change) also fall into this long-term structural paradigm.

This paradigm is taken to be reflected in rejection of innovative work by academic gatekeepers, as evidenced by (i) rejection of work eventually awarded Nobel Prizes in fields like Physics, Chemistry, Physiology and Medicine [12], as well as (ii) other processes related to academic research dissemination which have been found to constrain theoretical innovation [45], or (iii) perpetuate bias [18, 29], including confirmation bias [36] resulting in subjective bias as empirical evidence is sought out to support core tenets, and to disconfirm opposing tenets [35], which belies assumptions science necessarily progresses according to Popper’s [60] principles of falsification. Whereas the resource response paradigm relates to work within Kuhnian paradigms, where evidence is accumulated with the potential for it to accumulate and overthrow a paradigm [34], the structural paradigm is taken to reflect dominance of core tenets of scientific fields, which as described by Lakatos [35] defy paradigmatic change in that core theoretical tenets are immune to evidence suggesting change. This body of theory offers a perspective of the long-term structure of scientific fields which are taken here to be classifiable in terms of their slow response potential to disasters.

Market structure and incentive constraints are also perhaps associated with this paradigm, as innovativeness constrained by market structures (such as profitability challenges associated with pharmaceutical innovation in which returns to R&D are uncertain but high upfront investments are necessary), and the inherent need for profitability which may result in lack of investment in scientific problem solving in the first place for populations (markets) who cannot afford to pay. It is however not the place of this work to consider these issues here, but only to differentiate between these three temporal paradigms of disaster response in a way that is potentially useful, and which highlights potential for disaster management in real-time crisis situations to act as a laboratory for developing knowledge about real-time problem solving responses.

Arguably, the structural paradigm is therefore change constrained, and outcomes of its problem solving are subject to the forces science itself is nested within, such as social and economic forces which shape what it offers populations, and incentive systems of markets, which might under-prioritise social ends. It is possible emergent theory related to dramatic information and knowledgeflow enhancements associated with social media and crowd-sourcing in real-time contexts can also disrupt problems in structural response. However, key to this might be further research into how mechanisms of knowledge collection and analysis related to social media and crowd-sourcing can be made explicit and effective and efficiency increased. The field of crisis disaster management might hold the key to this knowledge development, and theory developed under these conditions of intense time constraints may ultimately offer problem solving or problem disruption potential in the other two temporal paradigms.

3.7. Typology of scientific types

Fig. 2 seeks to build on the above analysis, offering a typology of types of science and foci of types of change intent within scientific fields, as these relate to disaster management. The first type of science considered in Fig. 2 relates to disasters, or crises, which are taken to represent socially urgent and important research problems. Outbreaks of Ebola, Zika or lethal strains of influenza, or earthquake and tsunami response would be examples of these kinds of problems. Literatures within this area of science may be differentiated by change intent. Reflected in the disasters or crisis problem solving research seems to be a focus on radical changes in disaster management processes brought about by emergent technologies.

Arguably, it is at the nexus of radical changes and disaster research that new theory development is urgently needed, given
catastrophic consequences of such disasters. Incremental change research is taken to relate to disaster or crisis research problems which provide incremental changes in processes and systems, and change resistant research relates to research problems which are seemingly insoluble, or are difficult problems which yield little to disaster or crisis research. This typology broadly corresponds with the paradigms considered in Fig. 1, but with a more specific differentiation by intent of response (a more fine-tuned analysis) within these paradigms, as continua can be used to describe responses in each paradigm.

Arguably, being able to solve most disease outbreak problems and problems wreaked by catastrophic events such as tsunamis, earthquakes, hurricanes and the like in hours or days is an important goal, which can usefully shape literature categorisation. Advent of technological advances may offer increasing knowledge of mechanisms and processes which may ultimately provide breakthroughs in real time research problem solving capacity. A radical change research intent is therefore considered important, as breakthroughs in this area might have contagion potential to improve efficiencies and effectiveness in other areas of science and the change intent of research projects.

Change intent is taken here to reflect the explicit intention of researchers; to solve disaster crisis research problems in real time (without the luxury of time) may leave no other option but to focus on radical change. Probabilistic innovation is conceptually located in this research ‘space,’ where there are few resources to muster in the absence of time other than to use technology to maximise quality knowledge flows of inputs, analysis and problem solving (which if maximised can create a virtual laboratory for knowledge problem solving). Research focused on incremental change is taken to have as its intent incremental advances in science though changes in the way science is conducted. A change resistant focus of change intent is taken to represent research which holds precedent, or scientific norms in processes, to be the guiding principle of research work. Arguably, if research with real time implications can explicitly draw from radical change theory, this might enhance the probability of real time benefits.

Kuhn’s [34] conception of ‘normal science’ refers to research which solves problems but within a paradigm or explanatory framework, without challenging the assumptions of the theory or paradigm. Research with the intent of radical change in this type of science relates to radical advances but within established paradigms. Literature dealing with management of crises in real time is considered necessarily outside the ambit of Kuhn’s [34] normal science, as radical processes are required in order to create breakthroughs and real time research capability. However, even within this paradigm, there is perhaps a continuum of change intent. Radical change intent, although limited by paradigmatic assumptions, within this paradigm can lead to radical, or revolutionary outcomes [34], where transcendence of the paradigm can occur. Research within the resource response paradigm therefore has the potential to achieve paradigm transcendence. Arguably, disruption of this paradigm through theory developed in real time response can improve disaster responsiveness in theory development across the spectrum of research.

Structural science is taken to reflect the state of science described by Lakatos [35] in which science can seek to understand new developments in a way that supports its core ideologies, and resist change. Lakatos [35] relates analysis to Newton’s theory in physics, and how core theory is fundamentally resistant to change,
and new evidence. Within what is considered here Lakatosian science, are streams of literature which can be fundamentally wed to ideology or deep structures which can be at odds with Kuhnian normal science as the paradigm of Lakatosian science might not necessarily be aligned with scientific advances but premised on the maintenance of the field itself over and above scientific progress. In Lakatosian fields, radical change intent is taken to be typically concerned with field preservation, and change resistant intent is premised on maintaining the bedrock assumptions of fields in the face of contrarian evidence. Whereas Kuhn’s [34] normal science is taken to offer the potential for revolutionary science, or paradigm transcendence, structural science is not.

3.8. Disruption with its genesis in real time theory development

Fig. 3 offers a synthesis of the above analysis, and seeks to make explicit the disruptive influences of social media [1] and crowd-sourcing as crowdsourced R&D or expert problem solving [10,11]. These are just examples of the new age of technological advances enabling real time disaster response. Although the ‘natural laboratory’ of disaster crisis management is expected to offer the primary context through which theory development and theory testing can offer insights into the mechanisms through which real time problem solving can be enabled, contagion effects from advances in this literature are considered to transmit to recovery and structural change paradigms. In other words, theory

| Disaster management theoretical frameworks | Implications | Events | Contribution to probabilistic innovation |
|-------------------------------------------|--------------|--------|----------------------------------------|
| Complexity and jurisdictional, organisa-tional and other boundaries. Framework for critical social infrastructure and social infrastructure development [43] | Application of tenets of complexity theory relating to emergence, self-organisation, non-linearity, adaptiveness and connectivity. Mapping of hard and soft system infrastructure and building models of relationships [43] | 2003 Severe Acute Respiratory Syndrome | A social infrastructure needs to be created to support ongoing research into probabilistic innovation applied to management knowledge and solving knowledge problems under disaster conditions |
| Crowd-sourcing as a methodology for par-ticipatory network building, coordination and interactive crisis mapping supported by social media technologies [51] | Usahadi, non-profit software firm crowd-sourcing platform/Non-Profit Innovative Support to Emergencies, Diseases and Disasters (iOSTEDD) free open source platform/Collective coding groups, volunteer developer partnerships [51], Application and extension of probabilistic logics to information and knowledge sourcing [53] | 2012 New York Hurricane Sandy Disasters Chile, Japan and Haiti | Crowd-sourcing methodologies need to be developed to apply to research and development, termed crowdsourced R&D, and proactive crisis mapping and network building and coordination should be proactively pursued |
| Probabilistic approach to disaster manage-ment planning, modelling simulated losses and risk management [52] | Development of frameworks for application of crowd-sourcing to support management decision making [55], Lessons from how pandemic responses have been triggered by outbreaks, such as vaccine development [19] | Disasters in general | The probabilistic approaches need to be consolidated, and lessons applied to the development of probabilistic innovation applications, which offer a probabilistic rationale for developing real time disaster research capability |
| Development of frameworks for application of crowd-sourcing to support management decision making [55] | A common disaster management language needs to be developed, based on metadata to increase disaster resilience [23], More metamodeling can offer useful heuristics for thinking about real time crowdsourced R&D responses to disasters [44] | Developing a common language prior to disasters can be useful | Crowdsourced inputs can provide crowdsourced R&D with problem solving that relates specifically to how to manage decision making and how to manage con-gestion associated with high volumes of inputs |
| Lessons from how pandemic responses have been triggered by outbreaks, such as vaccine development [19] | Antivirals to treat seasonal influenza outbreaks can compromise their future use to treat pandemics [26] | 2009 H1N1 influenza pandemic [19] | Lessons derived from this work show how dramatic acceleration in R&D followed in the wake of a disaster. Arguably, if this acceleration can occur prior to disasters, the costs and consequences of disasters can be dramatically reduced. Probabilistic innovation seeks to create a radical ac-celeration of knowledge creation in real time, prior to disasters. |
| Disaster operations management; weighing information needed versus time available [23] | A common disaster management language needs to be developed, based on metadata to increase disaster resilience [23]. More metamodeling can offer useful heuristics for thinking about real time crowdsourced R&D responses to disasters [44] | Christchurch New Zealand earthquake/ Fukushima nuclear meltdown in Japan [44] | More metamodeling is necessary, in order to incorporate probabilistic innovation principles and crowdsourced R&D into disaster management models. By doing this formally, preparedness for disasters is enhanced. |
| Disaster management metamodels to in-corporate modelling techniques into comprehensive model of disaster re-sponse [44] | Antivirals to treat seasonal influenza outbreaks can compromise their future use to treat pandemics [26] | Viral pandemics [26] | Probabilistic methodology, applied to crowdsourced R&D, can incorporate feedback loops into the real time research process (these can be modelled within the system) |
| Importance of feedback loops; how disaster response can influence the course of current and future disasters [26] | Networks similar to GOARN can be useful for other aspects of proactive disaster management response | Human-Animal Interface cross-over outbreaks; avian virus subtypes H5N1 and H9N2, swine virus subtypes H1N1 and H3N2 [57] | Lessons from GOARN disaster manage-ment can be derived and applied to the development of a global probabilistic in-novation platform, and large scale in-vestment in crowdsourced R&D to devel-op theory and a methodology in service of disaster management. |
| Rapid identification, confirmation and re-sponse to global outbreaks; the Global Outbreak Alert and Response Network (GOARN), heightened alerts of human-animal interface (HAI) pandemic potential [57] | | | |

Table 1
Streams of literature relating primarily to real time response.
Disaster management theoretical frameworks | Implications | Events | Contribution to probabilistic innovation
---|---|---|---
Structuring interactions and managing community engagements by leveraging internet-based collaboration technologies [58] | Internet-based collaboration technologies leverage social interaction and expert-based communities on online platforms and between online community members and organisations; the use of innovation contests and money rewards to operationalise crowd engagement in all stages of the innovation process [58] | Potential applications to solving disaster problems by mobilising resources using innovation contests and rewards for real time inputs. | Advances in internet-based collaboration technologies can leverage crowdsourced R&D outputs; innovation contests can be used to harness the power of incentives and attain real time knowledge management capability. However, time is needed for this, and this literature can perhaps be more usefully approached as medium-term response.
Lessons from how pandemic responses have been triggered by outbreaks, such as vaccine development [19] | In wake of 2009 H1N1 influenza epidemic, innovation in vaccine development resulted [19]. The implications for disaster management derived from this suggest that if these advances could be spurred prior to outbreaks, benefits could be better captured | 2009 H1N1 influenza pandemic [19] | Lessons derived from this work show how dramatic acceleration in R&D followed in the wake of a disaster. Arguably, if this acceleration can occur prior to disasters, the costs and consequences of disasters can be dramatically reduced. Probabilistic innovation seeks to create a radical acceleration of knowledge creation in real time, prior to disasters. This relates to medium-term response. The ‘airport congestion’ analogy is derived from this literature; how to exponentially increase inputs into problem solving and knowledge management off a platform is akin to increasing the numbers of aircraft using an airport from tens to thousands. This is the key problem faced by probabilistic innovation research. If this problem could be solved, there is little standing in the way of solving biomedical and disaster problems, with applications from disease research to aging research. This problem is considered medium-term as theory developed here relates both to real time as well as structural paradigms, and is perhaps best located in this paradigm. Mapping of institutional, organisational and other boundaries prior to disasters is necessary. Developing large scale global probabilistic innovation initiatives requires knowledge of boundary spanning in knowledge management. Medium-term knowledge creation can contribute to real time response. Developing medium-term knowledge creation and problem solving capacity requires knowledge of events and innovative application of these technologies can enable real time response.
Shortcomings of traditional knowledge management systems (KMS); disjunctures between these systems and the unique complexity of each disaster where decision making needs to be in real time, and how social media can support ad hoc network formation [59]; social media in disaster risk reduction [1] | Disasters pose emergent challenges and problems, and real time decision making faces the problems of too much versus too little information; server-based disaster management software such as free open source Sahana Disaster Management System [59] | Disasters pose emergent challenges and problems, and real time decision making faces the problems of too much versus too little information; server-based disaster management software such as free open source Sahana Disaster Management System [59] | Disasters pose emergent challenges and problems, and real time decision making faces the problems of too much versus too little information; server-based disaster management software such as free open source Sahana Disaster Management System [59]
Boundary management of knowledge, based on information processing, shared meaning, political considerations [8] | Disaster management knowledge management requires cross-boundary engagement, and intense stakeholder engagement and inputs in real time | Useful knowledge of how boundary spanning knowledge management can be enabled under disaster conditions | Useful knowledge of how boundary spanning knowledge management can be enabled under disaster conditions
Event monitoring technologies [20] can be developed to contribute to real time crisis response. | Real time research capabilities can be generated by investment in preparation activities. | Insights from information gathering using event monitoring technologies derived from tunnels, bridges and buildings can be applied to other contexts of disaster management. | Insights from information gathering using event monitoring technologies derived from tunnels, bridges and buildings can be applied to other contexts of disaster management.

Table 2
Streams of literature relating primarily to resource response (Medium Term).
4. Conclusion

This paper sought to introduce certain arguments, proposing integration of crowdsourcing and social media technology may support a new era in knowledge management, offering important advances in the development of disaster management theory. The aim of the proposed approach is to support disaster efforts requiring research problem solving based on data which is only available after disasters unfold.

In support of these arguments, the concept of probabilistic innovation was introduced, which sought to explain how, using crowdsourced R&D and social media, exponential increases in problem solving inputs may increase the rate at which ideas, knowledge and information can transmit to research outputs and more effective real time disaster management. It was argued improving global frameworks for real time research and problem solving is particularly important in contexts in which the data needed for problem solving or crisis management is only available after onset of disasters. It is this need that probabilistic innovation theory and its methodology of crowdsourced R&D seeks to address. Another argument was also made, namely in order to radically accelerate socially important research, it is important to develop a field of research developing theory from experience of extreme disaster contexts as this can develop real time research data collection, synthesis and analysis capabilities. To do this, it is perhaps necessary to develop crowdsourced R&D capacity, harnessing data and information capabilities of social media, which in turn captures productivity enhancements associated with recent technology advances, allowing high volumes of expert problem solving inputs to be focused on solving crisis disaster management problems as well as a host of other research problems in real time. Hence, necessity is framed as driver of invention and innovation, and given real time constraints to problem solving, disaster management is perhaps a useful laboratory for theory development.

In order to highlight the need for a focus on real time disaster theory development, disaster literature was differentiated according to longstanding theoretical frameworks offering different perspectives of innovativeness of science, and scientific research. Drawing from Kuhn [34] and Lakatos [35] three paradigms were identified, with a special focus on the real time disaster paradigm, and the stream of literature related to probabilistic innovation was introduced, epistemologically associated with a vision of knowledge creation as emergent [21,40,32,33,48,49], and with the potential of harnessing data collection and analysis potential from very high numbers of participants, or populations, building on theory from citizen science [4], post-normal science [22] and participant-led research [54]. Arguably, further research could usefully build on the theoretical synthesis suggested in this paper, which might further guide exploration of causal mechanisms and channels through which emergent technologies like crowd-sourcing and social media information and knowledge collection and analysis might transmit.
to more effective real time disaster response and research problem solving.

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