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Towards coordinated self-organization: An actor-centered framework for the design of disaster management information systems

V. Nespeca *, T. Comes, K. Meesters, F. Brazier

Faculty of Technology, Policy and Management, Delft University of Technology, Jaffallaan 5, 2628 BX, Delft, the Netherlands

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ABSTRACT

Traditionally, disaster management information systems have been designed to facilitate communication and coordination along stable hierarchical lines and roles. However, to support coordination in disaster response, disaster management information systems need to cater for the emerging roles, responsibilities and information needs of the actors, often referred to as self-organization. To address this challenge, this paper proposes a framework for disaster management information systems that embraces an actor-centered perspective to explicitly support coordination and self-organization. The framework is designed and validated to (i) analyze the current practice of disaster information management, including the way changes occur through self-organization, and (ii) study how to design disaster management information systems that support coordination and self-organization within the current practice. A case study in Jakarta is used to modify and validate the framework, and to illustrate its potential to capture self-organization in practice. The analysis showed that analyzing the actors' activities through the framework can provide insights on the way self-organization occurs. Moreover, networking, preparedness and centralization were found to be key elements in the design of disaster management information systems with an actor-centered perspective.

1. Introduction

The rise of mobile technologies has made it easy to create and share information and to connect to communities or experts. In disaster response, this trend has opened up new possibilities to self-organize, coordinate and adapt. At the same time, this self-organization process has also introduced new challenges related to coordinating and orchestrating information flows [1–3]. When communication is disrupted, fragmented localized pockets or 'bubbles' of coordination and decision-making can arise (e.g. in different regions or hierarchical levels) as communities and responders are locally trying to fill an organizational and informational void. These 'bubbles' have been shown to be very stable, even when communication is restored, making it difficult to coordinate across them once they are formed [4].

Disaster management information systems (DMISs) able to support coordinated self-organization are aimed at fostering coordination (rather than the formation of fragmented 'bubbles') as well as self-organization. In this context, the challenge for DMISs is the volatility of actors' roles and responsibilities, and of the associated information needs. As such, information flows have to continuously adapt to *provide the information needed to the actors who need it.* Recent case studies on disasters show that supporting coordinated self-organization via information remains challenging [5,6]. As a result, information is often missing, inaccessible, or uncertain [7,8]. Moreover, the time pressure and continuous stream of information typical for disasters result in information overload, i.e., actors may not have the time to search for, or process information [9,10].

Due to the decentralized nature of self-organization, studying DMISs that can support coordinated self-organization calls for an *actor-centered perspective*. In the field of DMISs, there are several studies that model information diffusion [11,12], provide experimental insights on orchestrating information flows [10] or present case studies [7,8]. However, a conceptual framework is missing that embraces an actor-centered perspective and allows to systematically analyze and design DMISs. In this paper, an actor-centered framework is designed and validated that (i) enables the analysis the current practice of disaster information management, including the way changes occur via self-organization and the extent to which coordinated self-organization is supported, and (ii) provides the means to study how to design DMISs that support coordinated self-organization within the current practice.

* Corresponding author.
E-mail address: v.nespeca@tudelft.nl (V. Nespeca).

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This study adopts a Research Through Design strategy [13]. As disaster management constitutes a complex socio-technical system [7], the design approach by Brazier et al. [14] is adopted. The methodology is divided in five steps: (i) identification of key theoretical concepts and characteristics of DMISs based on literature (Section 2); (ii) development of requirements for the framework based on the concepts and characteristics (Section 3); (iii) framework design based on the requirements (Section 4); (iv) framework application to a case study and modification based on the findings (Section 5), (v) discussion of the framework validity related to its ability to enable the (a) analysis of the current practice of disaster information management, and (b) study of how to design DMISs within the current practice (Section 6).

2. Background

Insights from the fields of Multi-Actor Systems, Self-Organization, and Information Management are key to the design and development of DMISs with an actor-centered perspective. This section explores the related literature and identifies important characteristics and attributes of DMISs.

2.1. Multi-Actor Systems

Multi-Actor Systems research is rooted in Systems Thinking and focuses on complex socio-technical systems, in which the perspectives and interests of many stakeholders need to be considered. Multi-actor systems are composed of actors that act at least to some extent autonomously. Typically, there is no central authority that can coordinate all the actors. Therefore, to achieve a common goal, the actors have to coordinate by mutually adjusting their activities [15]. Humanitarian disaster response is a multi-actor system as a great diversity of autonomously operating *actors* assuming one or more *roles* in or for different *groups*, contribute to the response [7,16].

These *actors* are individuals that work in the field or remotely, and have personal characteristics that affect their work, such as knowledge, experience, skills and preferences [17]. For instance, an actor that has received professional training in urban search and rescue will act differently from an untrained community member who is rescuing his/her neighbours, even though their role is the same.

The *roles* of the actors are the positions they assume in a particular operation or process [18]. Roles are characterized by the associated responsibilities and capabilities, their information needs and access, domain of expertise, and status. Responsibilities are the specific tasks or duties related to a role [18]. Such responsibilities are often translated into norms and rules that describe how activities should be carried out. Capabilities refer to the activities that an actor *can* carry out as part of her/his role. Roles establish the types of problems to be addressed and therefore also the information needs [19]. Additionally, a role can in some cases give access to information. The same role can be carried out in different domains of expertise, e.g. an Information Management Officer can work in health or logistics. Roles are formal when explicitly mandated by an authority, while informal roles are usually assumed based on necessities [3,19].

Actors can belong to and have roles in different *groups*. A group is an ensemble of two or more actors that feel a sense of belonging [20]. Examples of groups are families, communities, and organizations [21]. The groups involved in a particular disaster response can change greatly depending on the characteristics of the disaster faced. Typically, the variety and number of groups, together with the complexity of their coordination, increases with the magnitude of the disaster, growing from involving solely local communities to including also other local, national and even international organizations and groups. Within groups the actors have weak or strong (social) ties constituting *networks* that enable them to exchange information and mobilize resources [22,23], possibly facilitated by information technology [24]. Groups *can* have *coordination structures*[1] that are based on established hierarchical and functional divisions of roles, with clear responsibilities and mandates following standardized operating procedures [25,26]. Structures can be within a group or across different groups. Additionally, the actors operate in an *environment* that can influence their activities [27].

Lastly, operations are the activities carried out by actors in the field that involve physical interaction with the environment. This includes for instance the movement of an actor through a disaster-affected area who is e.g. searching and rescuing victims of a disaster [21]. Operations could be intentionally meant to carry out other activities such as collecting information from actors in the field (e.g. aid needs of affected communities). Or, they could unintentionally trigger other activities, such as when information is unexpectedly found in the environment (e.g. the water level is rising).

In sum, the following characteristics and related attributes are identified:

- Actors: skills, experience & knowledge, preferences;
- Roles: responsibilities with related rules & norms, capabilities, domain of expertise, status (formal or informal), information (needs and access);
- Groups with their structures & networks;
- Environment;
- Operations.

2.2. Self-organization

Self-organization is the spontaneous emergence of order [28] or recognizable patterns in a system, in which multiple entities operate autonomously. In multi-actors systems, these entities are actors and self-organization takes place as a consequence of their decisions [29].

Self-organization is typical for disaster response [29]. Actors tend to change and assume new roles according to what is needed, even if this is not in line with their mandate, skills, or knowledge [19,30]. The groups and their structures and networks change as actors create new connections [24], form and join groups, and establish or modify structures within and across groups [31,32]. While self-organization has always been characteristic for disasters, it has become prominent in the last decades due to the introduction of new information technologies and social media [1,3]. Although self-organization provides an opportunity for faster and better tailored response, it can also create fragmentation and inefficiencies [3,4,21]. Coordinating the emergent activities of the actors and groups is hence essential for efficient disaster response and resilience [33]. Information is crucial for supporting coordination [7,27]. Whether actors obtain the information they need depends on the way information flows are collectively managed in the system [7,34]. Such information flows change through self-organization, e.g. when the actors adjust the way they share information [2,35]. In sum, role & structural change and networking (building new connections, and establishing or joining groups) are identified as self-organization and coordination activities, considered as a key characteristic of DMISs.

2.3. Information management

The goal of information management in disaster response is to orchestrate information flows so that the information required is provided to the actors that need it by the time they need it [19,34]. Much research has been carried out in the field of *information quality* to define what characterizes information needs [8,36]. Some of these characteristics have been included in the humanitarian information management principles adopted by the United Nations Office for the Coordination of

[1] Called structures from this point on.

Humanitarian Affairs (UN-OCHA) [37]: Relevance, Timeliness, Accessibility, Interoperability, Sustainability, Reliability, and Verifiability. Information is reliable if it is justified in terms of its content or source [38]. The volume and velocity of information can cause information overload, which makes it difficult for the actors to find the information they need [9,10], or even contributes to discarding or neglecting relevant information [4].

Information Management activities are all those tasks carried out to collect, evaluate, process and share information [34]. *Collection* occurs when actors intentionally or unintentionally acquire or receive information. Information *Evaluation* assesses, by looking at the information quality characteristics, the extent to which the information collected addresses an actor's information needs. *Processing* aims to produce information that can fulfill information needs. Processing activities could be filtering, aggregating, or translating information. Information *Sharing* is carried out to exchange information with others and *Storing* (or preserving) information for later use during or after a crisis.

The following attributes and their characteristics are identified:

- Information Management Activities: collecting, evaluating, processing, sharing & storing;
- Information Characteristics: Information quality (Relevance, Timeliness, Accessibility, Interoperability, Reliability, and Verifiability)[2], and Load;

3. Requirements design

The requirements design entails the formulation of the system mission and the related functional, behavioural and structural requirements [14,39]. The design process took place considering and building on the characteristics and attributes identified in Section 2 from an actor-centered perspective.

3.1. Mission

The mission is the purpose of the system. For DMISs that aim at supporting coordinated self-organization, the goal is to facilitate both coordination and self-organization via information. As information is key for coordination (Section 2.2), the mission of DMISs was derived from (i) the general goal of information management to provide the information required to the actors who need it, when they need it, and (ii) considering the characteristics of such information needs resulting from Section 2.3, leading to the following definition:

Mission of DMISs supporting coordinated self-organization*:* to provide relevant, reliable and verifiable information to the actors who need it, when they need it in an accessible manner.

3.2. Functional requirements

Functional requirements describe the functions that a system has to perform to fulfill its mission. To this end, the following requirements were designed by deriving the functions needed to achieve the desired 'information characteristics' as in Section 2.3.

Relevance: irrelevant information contributes to overload. The actors should therefore receive information that matches their intended use;
Timeliness: due to the dynamic nature of disaster response, information received and made available for the actors should be kept up to date to keep decision making and coordination attached to reality;
Accessibility (& Interoperability)[3]: information shared with the actors should be accessible for them in terms of language and format;
Reliability: information should be justifiable;
Verifiability: actors should have the means to determine the verifiability of information;
Load: the cognitive load associated with information should be limited.

Further, the groups and actors involved in disaster response change for different disasters, typically increasing in diversity and number with the magnitude or scale of the event (cf. Section 2.1). DMISs that support coordinated self-organization are required to do so for the broadest range of disaster events faced and the associated diversity of actors, roles and groups. As such, a framework for the design of DMISs is required to capture such diversity and the way it impacts the activities of the actors. The following requirement is inferred.

Diversity: the system has to cater for the great diversity of actors, roles and groups involved in and affected by the disaster, and to consider the way this diversity affects the activities carried out by the actors.

3.3. Behavioural requirements

Behavioural requirements define (i) the desired system behaviour and (ii) the KPIs for measuring the extent to which the desired behaviour is achieved. Therefore, behavioural requirements were designed from the functional requirements and developed into measurable system behaviours. Each behavioural requirement is derived from the homonym functional requirement.

Relevance: the degree to which the information that reaches the actors matches their intended use;
Timeliness: the degree to which the information received by actors is up to date;
Accessibility: the degree to which information is provided in such a way that the actor can easily use its content;
Reliability: the degree to which information is justified;
Verifiability: the degree to which the actors have the means to verify the information;
Load: the degree to which actors are loaded with information, possibly impairing them from retrieving relevant information.

3.4. Structural requirements

Structural requirements are the components of the system and their relationships put in place in order to fulfill the behavioral requirements. Structural requirements were derived by considering the characteristics and attributes of DMISs found in literature (cf. Section 2) that are required to achieve the desired behaviour. In the following paragraphs, the behavioural and functional requirements from which each of the structural requirements found is derived are shown in brackets.

In self-organizing response systems, actors cannot be associated with fixed roles as these can change (Section 2.2). Moreover, the characteristics of the actors also influence how particular roles are carried out (Section 2.1). Therefore, a framework for the study and design of DMISs that support coordinated self-organization is required to distinguish between actors and roles, and to capture their individual diversity. The following requirements are inferred.

Distinction between Actors and Roles (Diversity): Actors can change roles and assume additional ones. The way roles are carried

[2] Sustainability is not considered in this study as it is most relevant for longer term crises, which are out of scope for this study.

[3] Called accessibility from this point on.

out depends on the personal attributes of the actors who assume them;

Actors (Diversity): Actors are characterized by their Skills, Experience, Knowledge, and Preferences (e.g. willingness to share information);

Roles (Diversity, Relevance, Timeliness, Accessibility, Reliability and Verifiability): Roles are characterized by the Responsibilities and Capabilities to carry out specific activities, the Information needs (characterized by Relevance, Timeliness, Accessibility, Reliability and Verifiability) and access, the domain of expertise, and status (officially mandated or not).

Further, actors typically operate in groups (such as as NGOs, companies, communities, and families) that can present a wide diversity. As such, groups can be formally structured or not, and have informal networks. Structures can be of different types based on the presence of authority and on whether they cross the boundaries of groups or not (Section 2.1). These considerations lead to the requirements below.

Groups (Diversity): Actors can belong to and have roles in one or more groups. Groups are characterized by the sense of belonging of the actors who are part of it. Groups have networks and can have structures;

Distinction between Structures and Networks (Diversity): Structures define the formal way roles and their relationships are set within a group and the procedures to be followed (e.g. standards of operations). Networks are constituted by the informal connections (or ties) formed within groups and can be used to mobilize resources (including information) both within and outside structural relationships;

Structures (Diversity): Structures establish the roles in place, their relationships (in terms of the responsibilities, norms and rules that roles have towards one another), and the procedures adopted to address the envisioned contingencies. There are two types of structural relationships: vertical relationships establishing decision making authority and reporting lines, and horizontal relationships establishing lateral coordination across different functions (or domains). Structures can be intra-group or inter-group when such relationships cross the boundaries of groups.

Moreover, actors can perform a range of activities. These include adjusting their roles and groups according to arising necessities (Section 2.2). Additionally, actors manage information with the goal of fulfilling information needs (Section 2.3), but also operate physically in the environment. The environment can on turn influence the activities actors carry out (Section 2.1). The above leads to the following requirements.

Coordination (Relevance, Timeliness, Accessibility, Reliability, Verifiability): Activities that change the configuration of the (coordination) structures and networks: networking (new connections and groups are formed) and role & structural change (change in roles and their relationships). These activities are carried out by the actors to adjust to the current conditions and necessities;

Information Management (Relevance, Timeliness, Accessibility, Reliability, Verifiability): Activities such as collecting, evaluating, processing, sharing and storing information carried out by the actors e.g. to satisfy their own or other actors' information needs;

Operations (Relevance, Timeliness, Accessibility, Reliability, Verifiability): activities carried out by the actors in the field. These can lead the actors to perform further activities such as information collection (e.g. from the environment) or exchange (when other actors are encountered);

Environment (Relevance, Timeliness, Accessibility, Reliability, Verifiability): the external conditions that can affect the actors' activities.

4. Framework design

The iterative design process, in which requirements and designs were adapted and refined as needed, resulted in the framework design presented in this section. The design process focused on structural and behavioural requirements. First, the structural requirements were considered as an expression of the key characteristics, attributes and relationships needed to fulfill the behavioural requirements. Each characteristic was considered as an independent framework component, with its own attributes and relationships. The relationships among characteristics of the type 'can have one or more' or 'contains', determined the definition of vertical relationships or hierarchies among the characteristics (e.g. an actor can have on or more roles). Relationships 'perform' and 'affect' were considered as horizontal relationships. Secondly, the behavioural requirements were taken into account as the characteristic and attributes needed to assess the degree to which the functional requirements and mission are achieved. The following new definitions were introduced and used in the design process.

Information Management Structures: represent the ways roles and their relationships are organized, and the procedures adopted to perform activities that aim at addressing information needs;

Information Management Networks: are composed of the connections that actors have with other actors within and across groups, which enable information sharing activities;

Current Practice of Disaster Information Management: composed of the Information Management Structures and Networks in place within and across the groups involved in disaster response, together with the associated actors, their characteristics, roles they assume, and activities they carry out;

Analyzing the current practice: requires to (a) study its configuration in terms of the actors, groups, roles, IM structures and networks, (b) study the way changes occur in the system and how that leads to self-organization, and (c) assess to which extent the current practice supports coordinated self-organization via information;

Criteria for the assessment: criteria used to analyze the extent to which the current practice supports coordinated self-organization via information. Such criteria are designed based on the behavioural requirements and are: relevance, timeliness, accessibility, reliability, verifiability and load (see Section 3.3 for the definitions);

Designing DMISs within the current practice: entails modifying some of or adding to the information management structures and networks, groups, and roles in place, and possibly changing some of the actors' characteristics (e.g. through training, or awareness rising).

The design process resulted in the framework shown in Fig. 1. The framework can be used to *analyze* the current practice of disaster information management and to *study how to design* DMISs within the current practice.

5. Case study: Jakarta

Due to urbanization and land subsidence, Jakarta is increasingly suffering from coastal and riverine flooding [40]. In response to these floods, Jakarta has seen a rise in self-organization and the emergence of community organizations, often aided by social media. Floods in Jakarta are frequently of low to medium magnitude. These types of event can involve local, regional and national groups such as communities, governmental agencies and NGOs. However, floods of exceptional magnitude also occur in the city, as it was for instance the case in the years 2007 and 2013. In such major floods, also international actors can be involved in the response [41].

The wide diversity of actors and groups to be considered, together with the occurrence of self-organization via information, make Jakarta a pertinent case study to apply and validate the designed framework for

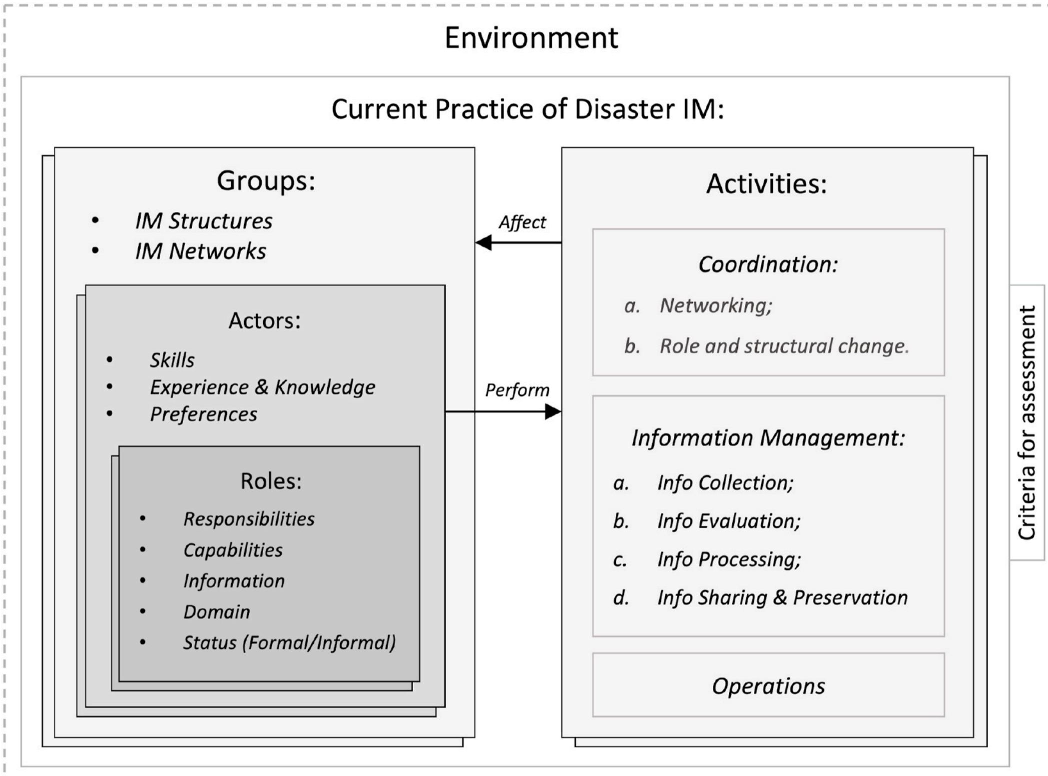

Fig. 1. Actor-centered framework for the analysis of the current practice of disaster information management and study of the design of Disaster Management Information Systems that support coordinated self-organization within the current practice. IM = Information Management.

the study and design of DMISs. The case study focused on national NGOs and local communities, but also international groups such as UN agencies (UN-OCHA) and other INGOs. In terms of communities, two of the most affected neighbourhoods in the city were chosen: Marunda (a coastal area frequently affected by coastal and riverine flooding) and Kampung Melayu (subject to frequent riverine flooding).

5.1. Data collection

First, an exploratory interview was carried out to design the field research, including finding relevant actors and communities to be included in the study. Based on the above, the data collection activities were planned. These included retrospective interviews and focus groups, but also documented sources of information. Retrospective interviews and focus groups allow participants to answer questions from their own experience. Our sampling strategy aimed at covering a broad range of different actors who have been active in disaster response. This strategy was used to limit the bias introduced by retrospection and to make the sample representative of the case study [42]. Events of different magnitude were covered, involving in some cases only local communities, and in others also national and international actors and groups. This choice was made to validate if the framework was able to cover the broad diversity presented by the case study, or if further adjustments were required. Additional participants were found during the the data collection based on suggestions by the participants themselves and through documented information such as emergency plans. These documents were also often indicated and shared by the participants.

The field study took place across October and November 2018. In total, 9 semi-structured interviews and 3 focus groups were carried out, involving 25 participants. The data collection with the local communities (Marunda and Kampung Melayu) took place in the neighborhoods and involved various members of the community including leaders, teachers, factory workers, and representatives of the local response team. The participants covered a broad range of demographics. Table 1 shows the types of participants, the number of data collection activities (interviews and focus groups) carried out for each of them, their total number and affiliation. More information on the type of data collected and how it was used can be found in Appendix A.

Table 1
Data collection, including the participant type, the number of interviews and focus groups carried out for each type, and the affiliation of the participants.

Participant Type	Interviews	Focus Groups (Participants)	Total Participants	Affiliation
Community Leader (CL)	2	0 (0)	2	Marunda, Kampung Melayu
Community Member (CM)	3	1 (4)	7	Marunda, Kampung Melayu, other
Community Responder (CR)	0	1 (8)	8	Marunda
Information Management Officer (IMO)	2	1 (4)	6	UN-OCHA[a], Pulse Lab Jakarta, IFRC[b]
Community Liaison (CLN)	2	0 (0)	2	UN-OCHA, Petabencana
Total Participants	9	3 (16)	25	N.A.

[a] United Nations Office for the Coordination of Humanitarian affairs.
[b] International Federation of Red Cross and Red Crescent.

The interview protocol followed four stages, each aimed at soliciting the interviewees to discuss the key characteristics of DMISs (see Table 2). The first two focus groups with Community Members and Information Management Officers followed the same protocol. However, the focus group with Community Responders aimed at explicitly capturing events of different magnitude. It was therefore structured according to three (flood) scenarios of increasing magnitude. In this

Table 2
Stages of the interview protocol, their contents, and & DMIS characteristics they target.

Stage	Contents	Targeted DMIS characteristics
Stage 1: Biographical	Introduction, Biographical Information & Role of the Interviewee	Actors, Groups, Roles, Environment
Stage 2: Situations	Selecting a specific (disruptive) event that triggered the need for information.	Environment, Activities of other actors
Stage 3: Information	Information needed to address the situations, as well as the information available that could be shared.	Information characteristics
Stage 4: Obtaining Information	How was the information obtained? From what sources and which activities, methods, and tools were involved.	Activities of the interviewee and other Actors, Groups, Roles and Environment

case, stage 1 was discussed in the beginning of the focus group, and stage 2 was represented by the flood scenarios. For each scenario, stage 3 and 4 were discussed.

5.2. Data analysis

The recordings collected during the interviews and focus groups were transcribed and analyzed using a platform for qualitative data management and analysis[4]. A mixed confirmatory and exploratory coding approach was adopted. First, an initial set of codes was developed based on the framework designed in Section 4. These were to be validated via their occurrence in the collected data. While looking for occurrences of codes from the initial set, open coding was also carried out in parallel to refine the initial codes and develop additional ones in an exploratory fashion.

The codes were divided into systems characteristics (first order) and their attributes and relationships (second order). The interviews were split among the authors so that each transcript could be autonomously coded by one author and cross-checked by another. Regular meetings contributed to the consistency of the coding scheme throughout data analysis. Table 3 shows the initial set of codes and how it was modified through open coding.

Next, sample quotes were extracted from the interviews to provide evidence for each of the attributes and relationships. Code counting was carried out to have an overview of the code instances found.

5.3. Findings

Compared to the initial 6 first order codes (characteristics) and 22 second order codes (attributes and relationships) distinguished from the framework design, no new codes were found via open coding. However, some discrepancies were encountered between theory and the data regarding the definitions assigned to some of the attributes and relationships (cf. Table 3). In such situations, the definitions associated with these attributes and relationships were modified accordingly.

The list of codes obtained in the data analysis, together with their updated definition is provided in Table 4. The table also includes (i) the code count and (ii) the sample quotes.

The Relevance and Timeliness assessment criteria were revised as shown in the following. *Relevance* is the degree to which information received by the actors matches their intended use (see sections 3.3). While this general definition is consistent with the current literature, the case study revealed that (i) the level of information aggregation (e.g. summarized for an area, or point by point) and (ii) its spatial location are

[4] https://www.dedoose.com/

Table 3
Evolution of codes and their description via open coding. The codes modified during the data analysis process are written in italics.

First Order: Characteristics	Second Order: Attributes & Relationships
Actors	Skills, Experience, Knowledge, Preferences
Roles	Responsibilities, Capabilities, Domain of Expertise, Status (Formal or Informal), and Information (needs and access).
Groups	Structures, and Networks
Activities	Networking, Role & Structural Change, Information Management, and Operations
Assessment Criteria	*Relevance*, *Timeliness*, Accessibility, Reliability, Verifiability, Load
Environment	Environmental cues

two key attributes in determining the relevance of information. For instance, when asked how information is presented in their crowdsourcing platform, the CLN from Petabencana mentioned how the information they collect is aggregated to match what is expected to be relevant for the user. Similarly, the user is able to select the location of interest. As a consequence, the definition associated with “Relevance” is modified as shown in Table 4.

The results from the case study hint to *timeliness* as the need to obtain information by the time it is needed. For instance, a member of the Kampung Melayu community stressed how flood warnings should reach the actors before it is too late for them to make a decision on whether to clean up after a flood or not. This definition contrasts the one that can be found in literature, that sees timeliness as a context independent attribute associated with the currency of information [8,37]. As an example, an up-to-date (or current) early warning that is received too late to evacuate would not be timely according to the definition proposed in this article. As a consequence, a new actor-centered definition can be deduced for the “Timeliness” attribute, as shown in Table 4.

6. Discussion

This section discusses the validity of the framework in terms of its ability to support (i) the analysis of the current practice of disaster information management in a case study area and (ii) the study of how to design DMISs that aim at supporting coordinated self-organization within the current practice (see Section 4). In the following, the examples from the field provided correspond to the quotes presented in Table 4. This section also showcases an application of the framework.

6.1. Analysis of the current practice of disaster information management

To validate the framework, it is first used to analyze the current practice of disaster information management in Jakarta with a specific focus on the Marunda and Kampung Melayu communities. In the first place, the framework is used to uncover and represent organically the configuration of the current practice of information management in the case study area. Secondly, the framework is used to study the way the current practice changes, possibly leading to self-organization. Thirdly, the current practice is analyzed via the assessment criteria in terms of its ability to support coordinated self-organization.

6.1.1. Analysis of configuration

This analysis was carried out by studying the actors, roles they assume, groups they belong to and the associated IM structures and networks. The analysis relied not only on the data collected in Section 5.1 and shown in Table 4, but also on the the documents found during the data collection. More specifically, these documents were used to confirm and expand the configuration of the current practice of disaster information management deduced from the interviews and focus groups (e.g in terms of the roles and groups in place).

A great diversity of **actors** can participate in managing information

Table 4
Findings from the field: list of characteristics, their attributes & relationships, code count and sample quotes. The attributes which definition changed via open coding are written in italics.

Char.	Attributes & Relationships	# Codes	Sample Quotes
Actors	Skills: ability to carry out activities within a given time. Skills can be transferable across roles.	30	'*I think it was a kind of a natural progression to then take some of that work and apply it (…) it just made a lot of sense. Because the skills were transferable*' UN-OCHA CLN
	Experience: procedural knowledge from previous disasters or training.	31	'*we just can wait for food from the public kitchen, from the volunteers. They will come*' Kampung Melayu CM
	Knowledge: non-procedural knowledge from info gathered during disasters or from education.	30	'*if the height in Depok is 3 m there will be no flood in here*' Kampung Melayu CL
	Preferences: personal preferences of the actors.	10	'*She would rather talk to people around here. There are some people here who always gather.*' Marunda CM
Roles	Responsibilities, Rules and Norms an actor should comply with given his/her role.	84	'*if somebody notices that the sea level rises, they directly inform it by sending text through WhatsApp*' Marunda CM
	Capabilities: activities that an actor can perform given a role.	64	'*if it gets worse, we will directly inform the sub-district government officer to directly handle it*' Marunda CL
	Domain (of Expertise): same role can be carried out in different domains.	24	'*I worked on the Ebola response, that was mostly on emergency information. (…) And, I worked in Greece (…) with refugees and migrants*' UN-OCHA CLN
	Status (Formal or Informal): availability of a mandate or not.	35	'*So yes, the government is helping us, but more than that communities (…) and also NGOs*'. Kampung Melayu CM
	Information: actors have information needs and access because of the roles they assume.	29	'*We can always provide you with information for example on assessment registry. What kind of assessment has been done, where is it, what sort of sector did they do the assessment*'. UN-OCHA IMO
Groups	IM Structures: roles, their relationships and procedures adopted within and across groups to perform activities with the goal of addressing information needs.	74	'*There are 17 community leaders here.*' Marunda CL
	IM Networks: ties or connections that actors have within and across groups, which facilitate information exchange.	100	'*There is a WhatsApp group for all community leaders (…) All people here, including regular people are in a WhatsApp group*'. Marunda CL
Activities	Networking: build new connections and create new groups.	40	'*sometimes after the meeting I need to chase people that have so much information (…). after the meeting I approach them to talk*'. UN-OCHA IMO
	Role & Structural Change: assume roles or change structural relationships among them.	13	'*I was becoming a reference for everyone for asking about mailing lists, who is working in certain area or what sort of maps are available (…) So that's the role that I have done.*' UN-OCHA IMO
	Information Management: Collect, Evaluate, Process and Share info.	132	'*I check information updates through Twitter. If, there is still no electricity I stay at home*'. Other Community CM
	Operations: activities in the field that require physical interaction with the environment.	37	'*We need the operational agencies to report to us (…) measuring and documenting observations from the field*'. IFRC IMO
Assessment Criteria	*Relevance*: the degree to which the information received by the actors matches their intended use, required level of aggregation, and spatial location.	50	'*When you open the map, you might not click on every point. But you would immediately have a sense of the areas that are flooded, enabling you to make decisions about areas to avoid*'. Petabencana CLN
	Timeliness: the degree to which information reaches the actors before the expiration of their information needs.	18	'*Sometimes we don't know whenever the flood finishes and then we can clean up our house. Then suddenly it floods again. We don't have any information*'. Kampung Melayu CM
	Accessibility: the degree to which information is in a language and format that can be used by the actors.	26	'*In a lot of the communities I've worked with there's no literacy and that's why face to face and oral communication is much more effective*' UN-OCHA CLN
	Reliability: the degree to which information is justified (e.g. based on the source).	16	'*I talked to my landlord, based on his experience from three or four years before the time, it can take a week.*'. Other Community CM
	Verifiability: the degree to which the actors have the means to verify the information (e.g. based on validity and consistency)	18	'*if we can get people on the ground to go and connect that virtual picture with the ground truth (…) we can validate what we think from the remote sensors*' IFRC IMO
	Load: the degree to which the continuous information stream and time pressure hinder the ability of the actor to find and process relevant information.	5	'*We don't overload the platform with too much information, because an overflow of information can cause confusion and paralyze the ability for residents to make actionable decisions*'. Petabencana CLN
Environm.	Environmental cues can cause actors to perform activities.	29	'*If she sees that a storm is coming, she will just run away to the safest place*'. Marunda CM

during flood response in the Marunda and Kampung Melayu communities. These include the community members and leaders, government officials or members of NGOs at the national and local levels, and IMO or CLN officers from international organizations. The high frequency of flooding in the case study areas has led actors at the national, local and community level, to develop disaster-related skills, experience and knowledge. For instance, community members know from experience that, if stuck on their roof during a flood, they will be delivered food. They have knowledge on the relationship between water heights at given river gates and flooding in their neighbourhoods. Community members also have skills such as using WhatsApp, that they can use to share information when required. Besides, skills, experience and knowledge, the actors also present personal preferences e.g. in terms of the actors that are contacted first when in need.

These actors assume **roles**, which could be captured through the framework together with their responsibilities, rules and norms (and associated types of activities), capabilities, information needs and access. Table 5 shows the results. For instance, the role “Affected Community” was found to be assumed by community members, leaders and responders, involves the information management responsibility of sharing potentially relevant information (e.g. flood warnings) with other actors in the affected community, provides the capability of sharing or retrieving information via the channels dedicated to the group (e.g. WhatsApp group of the Marunda community) or publicly available (e.g. Twitter media feed), the information needs of the role are associated with the information to be gathered (e.g. incoming floods), and information access is granted to group-dedicated and publicly available channels. Domain and status are not specified in Table 5 as the same role can be associated with different domains and statuses. For instance, the role “collector” could be performed in different domains (e.g. shelter or health). Additionally, this role is performed with a formal status by community leaders and responders, but also with an informal one by community members.

Three main types of **groups** were identified: (1) communities, (2) local, regional and national government agencies and NGOs with a mandate in disaster response, and (3) international organizations (NGOs, UN agencies). The structures and networks in place are shown in the following sections.

Government agencies rely mostly on hierarchical (or vertical) structures organized along the following administrative levels: national, provincial, cities, districts, sub-districts, administrative villages, community units and neighbourhood units [43]. At the national level, BNPB is the disaster management organization in charge of sharing emergency information with communities. The BPBDs take such responsibility at the provincial and district levels [44].

With regards to national *NGOs*, Petabencana runs a crowd-sourcing platform for flood-related information. This group relies both on structural relationships and network connections to share and manage information with other groups. Network connections are used to crowd-source information. To stimulate communities to use the information and collect more, a networking bot was designed with the role of collector and networker. This bot seeks new connections with actors who post flood-related information on social media, by re-directing them to the Petabencana crowd-sourcing platform. As for structures, a horizontal structural relationship with the local BPBD is used to share crowd-sourced information on flood occurrence and receive further information.

The formal structures in the Marunda and Kampung Melayu *communities* follow the administrative levels of Community Units (RWs) and Neighbourhood Units (RTs). Each RW and RT unit has a community leader with the role of group leader. RW community leaders have the role of liaisons between the local administrative village government and the RT units, while RT community leaders have the role of liaison between their RW leader and the community members. These structures are used to manage information internally (intra-group structures) and with other groups (inter-group structure e.g. with local government). As revealed by the community preparedness plan, additional structural arrangements found in the Marunda community are the local teams of community responders. Members of the community response teams have the role of Action Responder and provide aid in different domains (e.g. search and rescue, or food). Within the communities, also informal network connections play a crucial role. In the Marunda Community network connections are used to share information such as detected flood warnings and other information via a WhatsApp group. There is also a group only for community leaders (see Fig. 2). At a scale wider than that of a community, social media platforms (e.g. Twitter) are used as a channel to find and share information within and outside community networks.

International Organizations rely on structures associated with the cluster system [45]. This is a coordination mechanism suggesting a

Table 5
Roles observed, types of actor (case study participant) for which they were observed, and associates responsibilities, capabilities, information needs & access.

Role	Actor types	Responsibilities, Rules & Norms	Capabilities	Info. Needs	Info. Access
Affected Community (AC)	Comm. Member, Leader and Responder	IM: Share potentially relevant info (e.g. flood warnings) with other actors within the affected community	Share and search information locally and through public or dedicated channels	Warnings, Aid provision	Public (e.g. social media feed) and dedicated channels (e.g. WhatsApp group)
Collector (C)	Comm. Leader and Responder, Red Cross Volunteer	IM: collect and share info from the Environment and other actors; Operations: visits affected areas	Share and search information locally or through dedicated group channels.	Information from the field	Public and dedicated group channels (e.g. radio or WhatsApp)
Liaison (L)	Comm. Leader, CLN Officer	IM: collect info on other actors' information needs and availability, match info available and needs; Coordination: Networking	Request information on behalf of third parties	Other actors' info needs and availability	Dedicated group channels
Group Leader (GL)	Comm. Leader	IM: help request to higher level of hierarchy; Coordination: Structural change (delegation)	Can request information and help from higher hierarchical levels; Can delegate activities	Assessment Info; Coordination Info	Decisions from higher levels of Management
Information Manager (IMR)	UN-OCHA IMO	IM: evaluate and process information to make information products, store information in predefined locations; Coordination: networking	Store info in dedicated location	Info required for information products.	Dedicated information storage (e.g. contacts and assessment registry)
Information Hub (IH)	Petabencana Platform	IM: retain incoming information, share when requested	Store info in dedicated location	Specifically targeted	Third party info. products (e.g. estimated flood extent from BNPB)
Networker (N)	Petabencana Networking bot	IM: collect publicly shared information, process it to find the actors posting potentially relevant info; Coordination: Establish new connections with actors found	Process information shared in given social media platforms	Actors that are sharing potentially relevant information	Info. shared publicly in given social media feeds
Action Responder (AR)	Red Cross Volunteer, Comm. Responder	Operations: visit affected areas to provide Aid	Report on additional aid resources needed	Assessment & Coordination Info	Dedicated channels

Fig. 2. Community leader in Marunda, showing the WhatsApp groups used to exchange information with the community and other community leaders (RT and RW in the picture).

structural division into domain-specific clusters (e.g. shelter or health). Each of the clusters has a Cluster Lead Agency with a group leader and IMO(s) acting as information manager(s) within the cluster. An inter-cluster coordination group is also established (typically UN-OCHA) with dedicated IMOs. The Humanitarian Country team works on a mandate by the government to support humanitarian operations with regards to a specific crisis. The team is composed of the Humanitarian Coordinator as the group leader, and of the cluster group leads, and other nationals and international actors. The Humanitarian Coordinator has the the responsibility of establishing coordination structures and mechanisms tailored to the assisted nation. This is carried out in concert with the members of the cluster group leads and other national and international actors, all of which form the Humanitarian Country Team.

Fig. 3 shows the current practice of disaster information management in Jakarta through an integrated view of the actors, their respective (multiple) roles (as per Table 5), the (multiple) groups to which they belong, their structural relationships (vertical and horizontal) and network connections. This validates the ability of the framework to capture the configuration of the current practice of disaster information management of a considered case study through the analysis of actors, roles, and groups.

6.1.2. *Analysis of self-organization*

The previous section shows how analyzing the actors, roles and groups can provide a snapshot of the current practice at a given time. This section focuses on the *analysis of the activities* carried out by the actor, with the goal of uncovering how the practice changes during a disaster, and how those changes can lead to the spontaneous emergence of patters, or self-organization.

Examining the activities showed that an activity such as role change can be not only the choice of an actor, but also an emergent phenomenon resulting from multiple interactions with other actors. The UN-OCHA IMO found him/herself assuming the information hub role, not because of a direct personal choice, but as a result of gradually increasing information requests that external actors made. As the information requests increased, the information sharing activities of the IMO turned more and more into the responsibilities of an established (informal) role (see Table 4, row 'Structural & Role Change'). This phenomenon started when the actors become aware that the IMO had *knowledge* on the type of information available and also had *access* to many contacts because of its role. This shows how the characteristics of actor (e.g. knowledge) and roles they assume (e.g. information access) can play a role in self organization (e.g. emergent role change).

Besides interaction with other actors, also environmental factors can influence the activities carried out by the actors, possibly leading to self

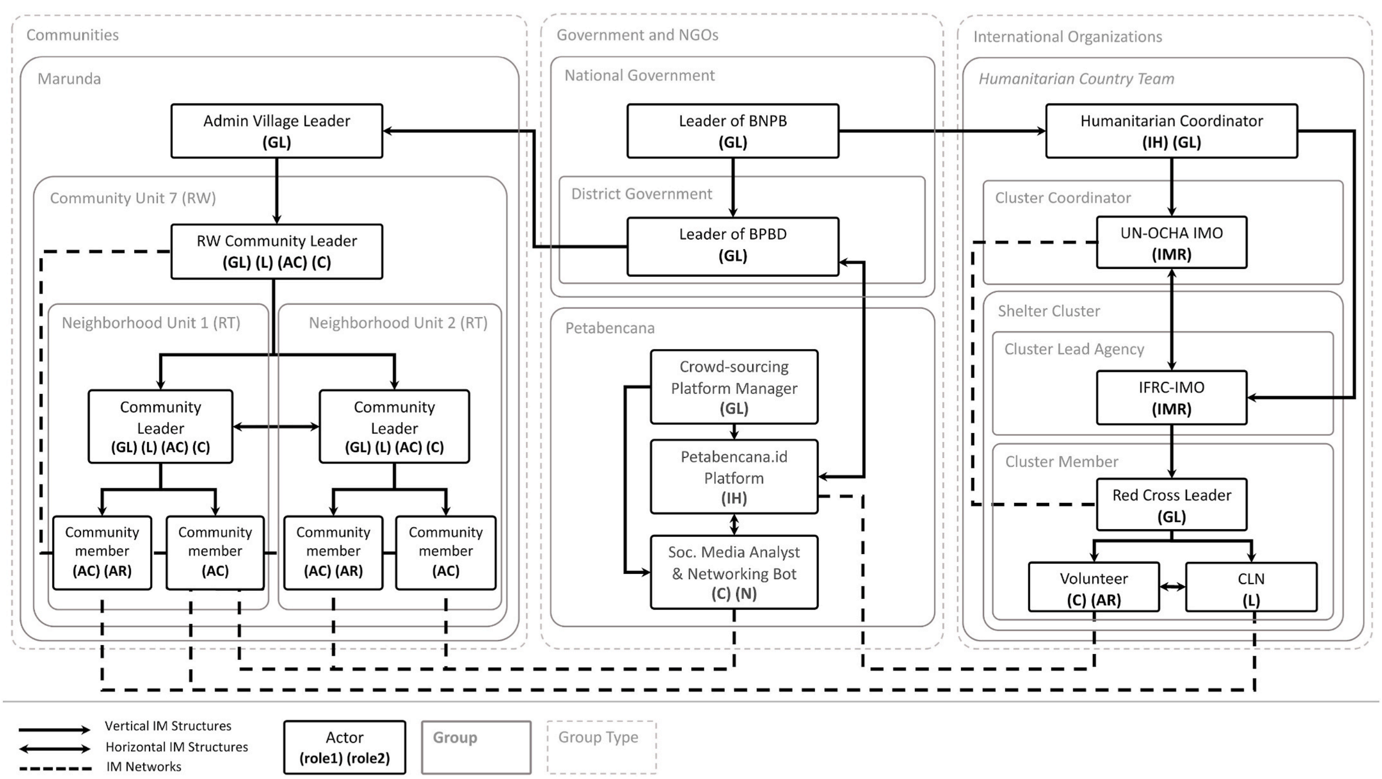

Fig. 3. Example snapshot of configuration of the current practice of disaster information management in Jakarta at a given instant of time, in terms of groups, Information Management (IM) structures and networks, actors, and their roles (according to Table 5). Some of the network connections across group types are plausible but hypothetical.

organization. For instance, the environment triggers coordination activities (specifically role change) when the members of the Marunda community are flooded and assume the role of affected community. However, no evidence was found that such change led to self-organization.

The study of activities showed how the framework can be used to study the way changes in the current practice can occur through emergent phenomena, thus validating the ability of the framework to study self-organization via information.

6.1.3. Analysis of support for coordinated self-organization

In this section, the assessment criteria designed in Section 4 and revised in Section 5.3 are used to analyze qualitatively the ability of the current disaster information management practice to cater for the information needs of the actors, thus supporting coordinated self-organization. In the following paragraphs, such an analysis is limited to the perspective of the communities.

The *Relevance* and *Timeliness* requirements are only partially fulfilled. On one hand, the system compensates to some extent for the lack of relevant and timely information via the use of IM networks. This takes place especially when structures become too rigid to cope with the actors' changing roles and information needs. An example is the early warning system run by community members in Marunda via a group chat. Social media is also used to share and retrieve information publicly available across groups e.g. on post-flood power outages. The NGO Petabecana attempts to facilitate information exchange across community and government groups by acting as an information hub, and by actively pursuing new network connections with community members active on social media.

On the other hand, it was found that actors are sometimes still missing the relevant and timely information needed. Often relevant information is available to other groups but it is simply not shared or received. For instance, communities upstream Marunda have access to river water levels, showing possible incoming floods in advance. However, this information is currently not being shared. In other cases, timeliness is still lacking. Community members stressed that in some cases they had to manually check for flood warnings. This way, timeliness depends on when actors actively look for information. Especially in unexpected situations (e.g. a second flood wave), the lack of push notifications reduces timeliness, limiting the ability of communities to make informed decisions and self-organize.

Reliability can be considered satisfied for the most part. In some cases, communities maintain that the information provided by peers (e.g. who have local knowledge or experience) is more reliable than that provided by official sources such as government agencies. For instance, when in need for information on the duration of power outages after a flood, one of the interviewees asked another community member who had knowledge and experience on the matter.

Verifiability was found of less concern from the perspective of the communities. Especially in the beginning of disaster response, the need for constant updates makes timeliness and up-to-date information more important than the ability to verify it. However, the actor have the means to verify information in the case of coastal flood warnings. For instance, this can occur through consistency across sources (when the same warning is shared by multiple community members) or when the information is directly checked by controlling the water level.

The *Accessibility* of information is considered to be fulfilled from the perspective of the communities. According to the participants, early warnings are provided in a simple language. Additionally, the Petabencana networking bot is designed to interact with the communities in a way that is easy to understand.

Load was not mentioned by the communities of Marunda and Kampung Melayu as a matter of concern. Additionally, the petabencana platform is designed to provide only key information, in order to avoid overloading communities.

The analysis uncovered the extent to which the current practice of disaster information management supports coordinated self-organization according to each assessment criterion. While communities were satisfied with the Load, Accessibility, Verifiability, and Reliability of information, Relevance and Timeliness were not completely satisfied. This showed that the current practice supports coordinated self-organization only partially.

The validity of the framework is confirmed as its assessment criteria provided the means to analyze to extent to which the current practice of disaster information management supports coordinated self-organization. The analysis also suggests that future designs of DMISs for the Marunda and Kampung Melayu communities should focus on the Relevance and Timeliness of information.

6.2. Study and design of disaster management information systems

Based on the analysis above, it was possible to understand some of the key variables to be considered in the design of DMISs within the current practice of disaster information management in a given case study, as showed in the following.

Networks can provide flexibility and facilitate information exchange outside structural relationships, especially when such structures are not in place or are too rigid. *Networking* is therefore key in enabling information exchange especially across actors and groups who could address each others' information needs, but do not have connections. Even though networking occurs 'naturally' among actors, the structures and roles in place can support networking across different groups. This can be implemented for instance through automated means (e.g. the Petabencana networking bot), or in other cases through meetings (e.g. as for those organized within and across clusters). The networks in place and the mechanisms for networking must be considered in the design of a DMISs.

The past history of disasters affects *preparedness*. In the considered case study, preparedness was reflected in the characteristics of the actors (i.e. their experience, knowledge and skills), the roles and responsibilities they assigned each other, and the structures and networks in place. Less prepared areas, in which the actors are not used to deal with a crisis or structures and networks are not in place are likely to require different designs of DMISs.

The structures in place can present different levels of *centralization*. They can be more centralized (as it was for the case of the government), or more decentralized (in the case there is not a structure, but only networks), or a combination of the two (as for the communities). While complete centralization has been criticized for managing disaster response, some level of centralization is required to ensure coordination [22]. Centralization is a factor to be considered in the design of DMISs.

This section demonstrates that the framework allows to study how to design DMISs within the context of the current practice of disaster information management. Indeed the networks in place, the centralization of the structures, their support for networking, and the preparedness of the actors are factors that characterize the current practice and have to be considered in the design of DMISs within such a practice.

This study could also be extended to understand how coordinated self-organization is supported by DMISs, thereby contributing to the resilience of the considered groups [33,46].

7. Conclusions

This paper fills a gap in the literature by proposing an actor-centered framework for the study and design of Disaster Management Information Systems (DMISs) that aim at supporting coordination as well as self-organization (here defined as coordinated self-organization). The framework is designed and validated to (i) enable the analysis of the current practice of disaster information management in terms of its configuration, self-organization and ability to support coordinated self-organization, and (ii) provide the means to study how to design DMISs within the current practice.

The mission, and the associated functional, behavioural and structural requirements for Disaster Management Information Systems were derived from theory (Section 3). The structural and behavioural requirements were used to design the framework and its use (Section 4).

The framework was then applied to the case study. This led to the modification of some of the assessment criteria within the framework. More specifically "timeliness" and "relevance" were adapted to the findings (Section 5.3). Moreover, the case study confirmed the framework validity to provide the means to *analyze the current practice* of disaster information management and *study how to design DMISs* within the current practice. First, the framework's ability to capture and analyze the wide diversity of actors, roles, groups composing the configuration of the current practice was validated (Section 6.1.1). Secondly, by analyzing the activities of the actors which lead to the spontaneous emergence of patterns, the framework was proven able to support the *study of self-organization* (Section 6.1.2). Thirdly, through the assessment criteria, it was possible to analyze qualitatively the extent to which the current practice supports coordinated self-organization (Section 6.1.3). Lastly, based on the analyses above, it was possible to uncover the importance of networking, preparedness, and centralization in the design of DMISs, confirming the framework's validity to support the study of DMISs' design (Section 6.2).

Given that the presented framework was validated with one case study, future research should focus on further validating and possibly expanding the framework based on different case studies. Additionally, the framework could be used to (a) study the underlying dynamics of actors, roles, groups, and information management structures and networks that lead to self-organization and (b) build a simulation environment that would serve as a research laboratory for testing and evaluating the extent to which different designs of DMISs support coordinated self-organization. For such an evaluation, the assessment criteria could be developed into quantitative rather than qualitative indicators of support for coordinated self-organization.

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.

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Appendix A. Data collection overview

Date	Location	Method	Participant Type	Affiliation
29/10/2018	Delft, The Netherlands	Exploratory Interview	Community Member	Indonesian Gov. Employee & Researcher
03/11/2018 to 05/11/2018	Central Jakarta	Semi-structured Interviews	Information Management Officer	UN-OCHA
			Information Management Officer	UN-OCHA and PulseLab
			Community Liaison	UN-OCHA
		Focus Group	Information Management Officers	IFRC
04/11/2018	East Jakarta	Focus Group	Community Members	Kampung Melayu Community
		Semi-structured Interview	Community Leader	
		Document: Community Emergency Plan	–	
06/11/2018 to 10/11/2018	North Jakarta	Semi-structured Interviews	Community Member	Marunda Community
			Community Member	
			Community Leader	
		Document: Community Preparedness Plan	–	
		Focus Group	Community Responders	
14/11/2018	Central Jakarta	Semi-structured Interview	Community Liaison	Petabencana

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