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An agent-based modelling study

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Vittorio Nespeca

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"Together we stand. Divided we fall."

Pink Floyd, Hey You - The Wall, 1979

"You, the people have the power - the power to create machines. The power to create happiness! You, the people, have the power to make this life free and beautiful, to make this life a wonderful adventure. Then - in the name of democracy - let us use that power - let us all unite! "

Charlie Chaplin, The Great Dictator, 1940

Contents

Acknowledgements

I once read that the closer you get to achieving your dreams, the harder it becomes to move forward. It is in those moments that we are truly tested—tested in our strength, our resolve, and our grit; in our ability to reach within ourselves to find the strength to continue, and also in our ability to draw from others, to receive and accept help, even when it doesn't come in the form we are most comfortable with. In pursuing the dream of becoming a scientist, I have certainly faced these challenges. Because of them, this PhD journey has been one of profound personal growth, as much as it has been one of professional development. There are so many people I have to thank for accompanying me on this path—those who supported me and believed in me no matter what; those who pushed me to improve, to learn from my mistakes, and to stay resilient through the highs and lows of research; and others still who offered a kind word or a friendly face when I needed comfort during difficult times. Summing up and thanking everyone who has helped me over these years is no easy task, as so many have played a role. But you can bet I'll try.

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1
Introduction

In this increasingly complex and chaotic world, fraught with systemic, compounding risks and disasters (or crises[1]), fostering disaster resilience is more crucial than ever [1, 2]. To achieve disaster resilience, actors must self-organize, respond, adapt, and transform to mitigate the impact of disasters [2–4]. This requires the collaboration of a wide range of heterogeneous actors and groups[2], including informal groups (e.g., local communities) and professional response organisations. Together, they must function effectively as a collective, demonstrating collective intelligence in their efforts to adapt, mitigate, transform, and respond [5].

1.1. Collective intelligence, coordinated self-organisation, and disaster resilience

Figure 1.1 shows the concepts and their relationships discussed in this section.

Collective intelligence is the ability of a system composed of different actors and groups to address complex problems in a changing environment[3] [8–10]. This ability is particularly relevant to foster resilience during disaster response operations characterized by volatile environments that change rapidly.

A system's collective intelligence hinges on its ability to coordinate resources, including information and knowledge, and direct them towards addressing specific problems [11, 12]. The need to coordinate resources is rooted in dependencies among the activities of different actors and groups within the considered system [13, 14]. Examples of such dependencies in disaster response systems include shared access to disrupted transportation infrastructure (e.g., an airport or seaport) or the need to collectively distribute response efforts across disaster-affected areas in a way that is proportional to local needs [15]. In this context, coordination involves managing dependencies among the activities of different actors and groups operating in disaster response [14, 16].

[1]The terms disaster and crisis are used interchangeably to refer to rapidly unfolding, disruptive events of natural origin, such as floods, earthquakes, and landslides.

[2]An *actor* is a member of a *group*.

[3]The environment comprises elements outside a group's boundary that influence the decisions made by its members, thus impacting the group's capacity to fulfil its objectives [6, 7].

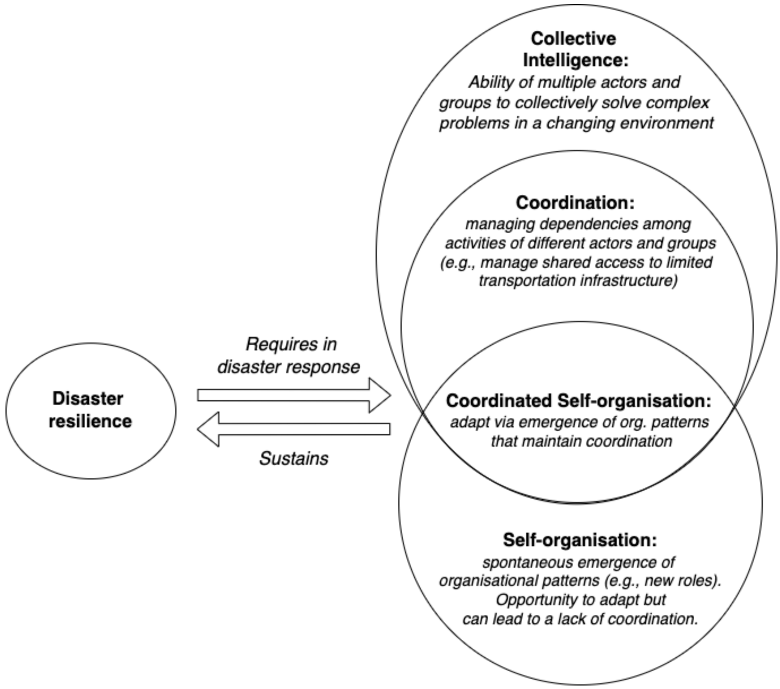

Figure 1.1: Overview of key concepts and their relationships.

During disaster response, the environment becomes highly volatile. All involved actors continually need to adapt their activities to the changing situation. The actors often adapt autonomously, even when centralized organisational structures dictate otherwise [17, 18]. This leads to a decentralized adaptation process, often resulting in the spontaneous emergence of new organisational patterns[4] such as the formation of new groups or changes in organisational structures and roles [15, 18, 25, 26]. This process, by which the operational patterns emerge, is known as self-organisation [27–29].

While self-organisation enables a system to adapt during a disaster, it also presents significant coordination challenges. Actors may neglect coordination or limit it to certain groups, excluding others and creating fragmented pockets of coordination [30]. This fragmentation is particularly evident at the boundary between professional response organisations and communities [15, 18, 31].

While fragmentation can support coordination in routine operations that require

[4]A pattern is a regularity that can be observed in reality, e.g., the flocking of birds. Patterns can emerge through interactions among different parts of a system [19]. The flocking behaviour of birds, for example, can spontaneously arise from interactions among individual birds [20]. Organisational patterns are ways of performing and dividing tasks among actors. While such division is typically the result of top-down decision making regarding hierarchical structures, mandated roles, and standardized procedures [21], organisational patterns can also emerge through interactions among actors. This can lead e.g., to the emergence of new groups [22], informal leaders [23], or roles [24].

a predefined division of roles [17], it disrupts coordination in non-routine operations that demand mutual adjustment, as is often the case in disaster response [25, 32]. This lack of coordination, in turn, undermines collective intelligence and resilience.

To support collective intelligence and resilience during disaster response, it is imperative for actors and their groups to self-organize in a way that maintains effective coordination. Actors need to align their activities through a process defined in this thesis as *coordinated self-organisation*. A system characterized by coordinated self-organisation can restructure and adjust its organisational patterns through an emergent, decentralized process, allowing it to adapt to changing environmental demands and the evolving needs of its actors and groups, while managing the dependencies among their activities.

1.2. Information sharing for coordinated self-organisation

Effective information sharing among actors from different groups is crucial for supporting coordinated self-organisation and collective intelligence [12]. It enables actors to monitor relevant environmental changes and shifts in the activities of other actors and groups that require attention, thereby allowing a system to self-organize in response to its environment while maintaining coordination [16, 28].

Yet, effective disaster information sharing during crises presents significant challenges. As groups navigate the rapidly changing dynamics of disasters, their organisational structures and roles are in constant flux due to self-organisation [25, 33, 34]. Consequently, the information needs of the actors evolve continuously, making them a ’moving target.’ This ongoing change requires the orchestration of information flows to be highly adaptive and responsive. To ensure that critical information reaches the appropriate actors and groups in a timely manner, it is imperative that information sharing strategies are flexible and capable of adjusting to the ever-changing demands of the disaster environment [32, 35]. Achieving this flexibility remains a challenge [36, 37].

Additionally, the volatility of the environment and continuous influx of information (including large amounts of irrelevant information) during disasters lead to information overload, preventing actors from effectively searching for or processing information [38, 39]. As a result, information is often unavailable, inaccessible, or unreliable [26].

In sum, key challenges in fostering effective inter-group information sharing that supports coordinated self-organisation in crisis response operations are:

1. flexibly adapting information flows to the actors’ shifting information needs;

2. avoiding information overload.

1.3. The need for an actor-centred perspective

Traditional information-sharing strategies are often inadequate for addressing the challenges outlined in the previous section. First, these strategies are designed to support communication and coordination within stable organizational structures, where roles and information needs remain relatively fixed. Second, they do not account for the need to adapt information flows to prevent actors from becoming overloaded with information.

To investigate novel information-sharing strategies that can adjust to shifting information needs while managing information load, it is crucial to understand and leverage the self-organized and emergent mechanisms leading to changes in roles and information needs and to information load. Studying such mechanisms requires accounting for the information-sharing behaviour of individual actors at the micro level [38, 40]. It also involves examining the potential complex relationships among these micro-level factors and (a) information sharing practices within the groups or organisations to which the actors belong at the meso level, as well as (b) the decision-making environment (e.g., its volatility) and the information sharing practices across groups at the macro level [41, 42]. To this end, this dissertation adopts an actor-centred approach to the study of disaster information sharing (called Actor-centred Disaster Information Sharing or ACDIS), emphasizing the implications of micro-level behaviour on inter-group disaster information sharing.

1.4. The role and promise of Informational Boundary Spanners

One promising way to address the challenges outlined in Section 1.2 and support coordinated self-organisation is to understand and leverage the emergence of actors who facilitate information sharing across different groups by acting as information exchange hubs. These actors are referred to as Informational Boundary Spanners (IBSs) in this dissertation[5] [26, 45].

Understanding the mechanisms behind the emergence of IBSs that effectively convey information across groups is crucial for designing strategies that enhance inter-group disaster information sharing and support coordinated self-organisation [24]. However, these mechanisms remain poorly understood in the volatile environment of a disaster. Studying the emergence of IBSs requires examining the complex interplay between micro-level individual behaviour of actors, meso-level intra-group information-sharing practices, and macro-level environmental characteristics and inter-group information-sharing practices [24, 42, 46]. Given this complex and multi-level interplay, the phenomenon of IBS emergence can be studied through the lens of ACDIS (Cf. Section 1.3).

[5] IBSs are actors, specifically human individuals. IBSs can work in tandem with boundary objects (e.g., maps, digital platforms, and ICT) to facilitate inter-group information and knowledge exchange [24, 43]. While boundary objects and their interplay with IBSs are a key subject of study in disaster response systems [44], this thesis focuses on IBSs and not on boundary objects.

1.5. Towards understanding and leveraging IBSs emergence through the actor-centred perspective

Numerous studies have highlighted the potential benefits of examining disaster information sharing from an actor-centred perspective [26, 39, 41, 47, 48]. Some of these studies rely on case study research [26, 41], others on Agent-Based Modelling (ABM) [47, 48], and others on disaster simulation exercises [39, 41]. Despite these advances, a systematic approach to studying ACDIS that supports coordinated self-organisation and resilience in disaster response is currently lacking. In order to develop such an approach, the following research gaps need to be fulfilled.

First, to systematically study and individuate information sharing mechanisms that facilitate coordinated self-organisation, it is essential to define its key characteristics and requirements, including relevant performance metrics. However, the lack of an actor-centred conceptual framework that captures these characteristics and requirements hinders the systematic, actor-centred study of disaster information sharing.

Second, agent-based modelling and simulation offers a powerful means for systematically studying actor-centred information sharing. However, even though fragmentation and the need for effective information sharing are particularly pronounced at the boundary between professional response organisations and communities [15, 18, 31], there is a lack of Agent-Based Models (ABMs[6]) of ACDIS that account for information sharing between these two groups.

Third, developing actor-centred ABMs requires, by definition, an empirical understanding of individual, group, and system-level behaviour, for which qualitative case study research is a promising approach [49–53]. Qualitative research is promising for studying ACDIS as (a) gathering sufficient quantitative data on disaster response operations (e.g., for hypothesis testing through surveys) is often difficult, and (b) for new phenomena like ACDIS, the lack of existing knowledge makes it challenging to formulate hypotheses to be tested quantitatively. In such situations, a qualitative and exploratory approach is more suitable [54]. Among different methods that rely on qualitative research, case study research was chosen because ACDIS involves complex interdependencies between context and phenomenon, which cannot be clearly separated, and because the number of variables likely exceeds what can be supported by the available cases, making statistical generalisation unfeasible [55].

One of the advantages of using case study research in combination with ABM is the ability to rigorously compare results and findings across multiple cases [49, 53]. To this end, it is essential to both learn from and flexibly account for the uniqueness of each individual case while also enabling cross-case comparison—two objectives that often conflict and between which a balance must be struck. Yet, a rigorous methodology that balances cross-case comparability with

[6] In this thesis, 'ABM' is used as an acronym for both Agent-Based Modelling, referring to the modelling paradigm, and Agent-Based Model, referring to a computational model that relies on the Agent-Based Modelling paradigm.

the flexibility to capture different case studies is currently lacking. Further, studying ACDIS mechanisms through ABM may require the develop and use of different models with both theoretical and empirical purposes [56]. Yet, a methodology that offers the versatility to develop both empirical and theoretical ABMs for studying a phenomenon of interest is also missing.

Finally, while ABMs of ACDIS can simulate the emergence of IBSs, they are insufficient for studying and understanding the mechanisms underlying this emergent process. A quantitative method is needed to measure the emergence of effective IBSs from an actor-centred perspective using simulation results. However, such a method has yet to be developed.

These considerations lead to the formulation of the research objective and research questions of this thesis.

1.6. Research Objective

The objective of this thesis is to systematically explore actor-centred information sharing processes that support disaster resilience by fostering coordinated self-organisation.

1.7. Research Questions

Given the above-mentioned research objective, this study aims to answer the following research question (RQ):

How can actor-centred disaster information sharing that supports coordinated self-organisation be systematically analysed?

This question is divided into the following sub-questions.

RQ1) *Can an actor-centred conceptual framework be designed to capture the characteristics and requirements for disaster information sharing that supports coordinated self-organisation, and how?*

RQ2) *Can an ABM be developed for supporting the study of actor-centred disaster information sharing across groups, and how?*

RQ3) *Can a methodology be designed to develop ABMs for supporting the study of a phenomenon of interest through qualitative inquiry, and how?*

RQ4) *Can a quantitative method be designed to measure and understand the emergence of effective IBSs from an actor centred perspective, and how?*

1.8. Research Overview

This section describes the research strategy and the instruments employed to answer the research questions. It also introduces the research project that funded and supported this PhD thesis.

1.8.1. Research Strategy:

The research strategy adopted is Research Through Design [57, 58]. This research strategy focuses on a particular design goal that drives the generation of new knowledge. At the beginning of the research process, background knowledge (e.g., from the literature and experience) is used to define the design goal and start the first design iteration. Then, further iterative design actions are carried out, progressing in the direction of the goal. During each iteration, additional knowledge can be considered, and new knowledge can be generated. Such new knowledge can also be taken into account in the next iterations, thus building towards the design goal [59].

Each iteration includes the following phases: selection, design, evaluation, reflection, and repetition [60]. The iteration starts with a selection process in which a research problem is chosen based on the design goal. In the first iteration, this occurs based on the background knowledge. But, also new research problems can be encountered in the following iterations that need to be selected [58]. Then, a design phase follows, during which a particular artifact is produced. Examples of artifacts for this research include a conceptual framework for capturing ACDIS, empirical and theoretical agent-based models, or information sharing strategies. Next, the design is evaluated. In such a process, new insights are gained. Based on the results of the evaluation, a reflection takes place on the progress made, to be considered in the next iteration.

1.8.2. Research Instruments

The following research instruments were used for this PhD thesis.

- **Narrative literature reviews** are carried out to inform the design requirements for ACDIS and of the associated conceptual framework, and to guide the design of ABMs (e.g. based on previously existing theories, algorithms, frameworks, and agent architectures).

- **Interviews and focus groups** are adopted to collect the data necessary to study disaster information sharing across multiple groups through an actor-centred perspective.

- **Content analysis** was used to examine data obtained from interviews and focus groups (textual transcripts). This method served to (a) confirm, validate, and expand the requirements and conceptual framework developed from the literature and (b) inform the development of ABMs to study disaster information sharing from an actor-centred perspective.

- **Agent-Based Modelling & Simulation** is used to formalize findings from interviews, focus groups, and literature and to support the formulation and testing of micro-meso-macro mechanisms for the emergence of information sharing among the different actors and groups operating in disaster response.

1.8.3. Research Project

This dissertation was partially performed in the context of the COMRADES project. COMRADES was a three-year project to create an open-source, community resilience platform financed by the European Union Horizon 2020 Research and Innovation Framework Programme H2020-ICT-2015. The project started in January 2016 and finished in December 2018. COMRADES aimed to build a platform that acts as an information-sharing hub[7] among different groups to support coordinated self-organisation and resilience. Professional responding organisations, and online and local communities can share and look for relevant information. The platform is integrated with existing ICT tools such as social media that are already being used on a daily basis by the different actors involved in disaster response. This strategy enables easier access for the actors who want to make use of the platform. Further, to support actors in finding information that is of good quality several automatic information processing mechanisms are introduced e.g. categorize and verify information, and add context-related hyperlinks to increase relevance, reliability, and accessibility.

The project provided the opportunity to design the requirements for a conceptual framework focused on ACDIS. It also enabled the development of ABMs of ACDIS. The framework and ABMs were further refined and validated through field research and qualitative studies with communities and professional responders, covering case studies in The Netherlands, Belgium, Nepal, and Indonesia (Jakarta). The project also opened opportunities for further research, such as collaborations with the University of Indonesia and the NGO Petabençana.

Several deliverables were written summarizing the results of this project. The author of this thesis contributed to two of these deliverables, which focused on evaluating the COMRADES platform with end users, including communities and professional response organisations [61, 62].

1.9. Thesis Outline

This thesis includes 7 chapters. The subsequent chapters are organized as in the following.

- **Chapter 2** analyses the literature on ACDIS to motivate the gaps and research questions addressed by this thesis. First, it discusses the literature on ACDIS and its contribution to disaster resilience, emphasizing the need for a conceptual framework. Second, since ABMs are essential for studying actor-centred information sharing, the chapter examines the literature on ABMs in this context, revealing a current lack of such models. Third, the chapter reviews methodological approaches for developing ABMs through qualitative inquiry, identifying the need for a methodology that balances cross-case comparability with flexibility to accommodate different cases,

[7] The platform developed in the project was intended as a boundary object rather than an IBS. However, research conducted as part of the COMRADES project provided insights into the emergence of IBSs, which sparked my interest and motivated me to study IBSs instead of boundary objects.

while ensuring versatility for various modelling purposes. Finally, the chapter examines the role of IBSs in disaster information sharing from an actor-centred perspective, highlighting the need for methods to measure and understand their emergence.

- **Chapter 3** builds on Chapter 2 to propose a new rigorous methodology to develop a conceptual framework and ABMs for studying a particular phenomenon or process of interest (i.e., ACDIS) through qualitative case study research. This methodology is designed to balance cross-case comparability with the flexibility to capture diverse cases and phenomena. Furthermore, it aims to be versatile, supporting the rigorous development of both empirical and theoretical ABMs. The methodology includes two phases. The first focuses on developing requirements and a conceptual framework that is centred on the phenomenon of interest based on existing theories and qualitative insights from one or more case studies. In the second step, the framework and existing generic models are used to inform the design of empirical or theoretical ABMs aimed at studying the considered phenomenon of interest. This chapter provides a foundation for answering RQs 1-3 by providing a methodology to develop conceptual frameworks and ABMs for studying ACDIS.

- **Chapter 4** This chapter designs a conceptual framework for ACDIS following the steps of the first phase of the methodology developed Chapter 3. It reviews literature to establish the *characteristics* of ACDIS. It then designs the *requirements* for actor-centred information sharing based on the characteristics. These requirements are subsequently validated and refined through the case study of Jakarta. The chapter concludes by illustrating the development of a conceptual framework for ACDIS, based on the previously developed, validated, and refined requirements. This chapter answers RQ1. This chapter also validates the first phase of the methodology presented in Chapter 3, thereby contributing to answering RQ3. First, it demonstrates that this phase enables the rigorous development of a conceptual framework for the phenomenon of interest (ACDIS). Second, it shows that this phase of the methodology provides the flexibility to capture the phenomenon of interest through a novel conceptual framework when such a framework is unavailable.

- **Chapter 5** As prescribed by the second phase of the methodology developed in Chapter 3, the conceptual framework designed in Chapter 4 is applied to one or more case studies (Jakarta in this case) to develop an ABM of actor-centred information sharing. The application of the framework reveals the system's configuration (e.g, the actors and groups operating in disaster response and their information sharing activities), system's change (including a *candidate mechanism for the emergence of IBSs* through self-organisation), and system's performance (the extent to which good quality information reaches those who need it thus supporting coordinated self-organisation). These results are structured and interpreted through a generic model (i.e.,

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the Generic Agent Model), to inform the systematic development of an empirical ABM of ACDIS in the Marunda Community of North Jakarta. The modelling purpose of this ABM is that of being a non-reductionist description aimed at informing further research in actor-centred information sharing in disaster response. This chapter results in the development of an ABM to study ACDIS, thus answering RQ3. This chapter also validates the second phase of the methodology, demonstrating its rigour, versatility, and ability to balance cross-case comparability with the flexibility needed to capture the nuances of individual cases. It then discusses the methodological findings from Chapters 4 and 5, illustrating the rigour, versatility, and balance between flexibility and comparability provided by both phases of the methodology introduced in Chapter 3, thereby addressing RQ3.

- **Chapter 6** presents the development of a method for measuring the emergence of IBSs from an actor-centred perspective. Following this, a new ABM is developed, building on the ABM and candidate mechanism for IBSs emergence respectively developed and identified in Chapter 5. This new ABM, combined with the method for measuring IBSs, is used to study whether the candidate mechanism actually leads to the emergence of IBSs that promote effective information sharing across groups. The chapter concludes with recommendations for designing actor-centred information sharing strategies that leverage the IBSs emergence mechanism to support effective information sharing and coordinated self-organisation in disaster response. This chapter addresses RQ4 by developing and validating a method for measuring and understanding the emergence of IBSs from an actor-centred perspective.
- **Chapter 7** discusses how the findings of this thesis address the research questions posed in this introduction, provides implications for practice, and outlines directions for future research.

A graphical summary of the thesis outline is shown in Figure 1.2. Table 1.1 shows for each chapter in detail the methods employed, contributions provided, and research questions addressed.

1.10. Publications related to this thesis.

1. Nespeca, V., Comes, T., Meesters, K., Brazier, F., 2020. Towards Coordinated Self-organisation: An actor-centred framework for the design of Disaster Management Information Systems. International Journal of Disaster Risk Reduction 101887. [Chapters 3, 4 and 5]
2. Nespeca, V., Comes, T., Brazier, F., 2023. A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry. JASSS 26, 10. [Chapters 3, 4 and 5]
3. Nespeca, V., Comes, T., Brazier, F., 2022. Share: bottom-up disaster information management v1.0.0. CoMSES. https://doi.org/10.25937/3dbz-qv52 [Chapter 5]

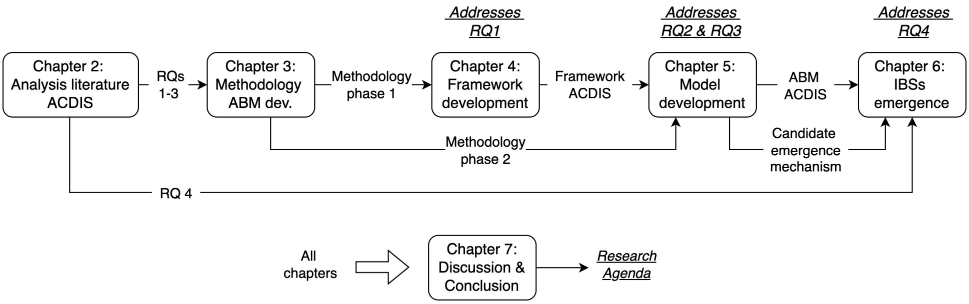

Figure 1.2: Thesis outline: overview of the chapters and their contribution to answering RQ1, RQ2, RQ3, and RQ4. ACDIS = Actor-centred Disaster Information Sharing.

Chapter	**Methods**	**Contributions**	**RQ addressed**
Chapter 2	Narrative literature review	Motivates research gaps & associated RQs 1-4	-
Chapter 3	Research through design	Methodology for developing a conceptual framework (Part 1) & an ABM based on the conceptual framework (Part 2) for a phenomenon of interest through qualitative case study research	Foundation for **RQs 1-3**
Chapter 4	Narrative literature review, interviews, focus groups, content analysis	Actor-centred conceptual framework for disaster information sharing supporting coordinated self-organisation	*Answers **RQ1***; Contributes to **RQ3** - Validated methodology part 1: rigorous in building a conceptual framework; flexibility to capture a novel phenomenon of interest
Chapter 5	Content analysis, agent-based modelling and simulation	Empirical (descriptive) ABM of ACDIS for the Marunda neighbourhood in North Jakarta; Candidate mechanism for the emergence of IBSs	*Answers **RQ2***; Concludes ***RQ3*** - validated methodology part 2: (a) rigour in translating qual. data into ABM rules; (b) balanced flexibility and comparability; (c) demonstrated versatility in developing empirical ABM
Chapter 6	Agent-based modelling and simulation	Theoretical ABM of ACDIS to simulate IBSs emergence; Quantitative method to measure and understand the emergence of IBSs (based on simulated outcomes)	*Answers **RQ4***
Chapter 7	-	Discussion concerning the way RQs 1-4 are addressed by the thesis, thus answering the overarching research question; Summary of contributions of the thesis; Implications for practice; Research agenda on Collective Intelligence for RE-silience (CI4RE)	Synthesis

Table 1.1: Overview of methods, contributions and research questions addressed for each chapter.

4. Nespeca, V., Comes, T., Brazier, F., Learning to connect in action: Measuring and understanding the emergence of boundary spanners in volatile times.

Collective Intelligence, *Submitted* [Chapter 6]

REFERENCES

[1] K. Eshghi and R. C. Larson. “Disasters: lessons from the past 105 years”. In: *Disaster Prevention and Management: An International Journal* 17.1 (2008), pp. 62–82.

[2] J. Rockström, A. V. Norström, N. Matthews, R. Biggs, C. Folke, A. Harikishun, S. Huq, N. Krishnan, L. Warszawski, and D. Nel. “Shaping a resilient future in response to COVID-19”. In: *Nature Sustainability* 6.8 (2023), pp. 897–907.

[3] F. H. Norris, S. P. Stevens, B. Pfefferbaum, K. F. Wyche, and R. L. Pfefferbaum. “Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness”. In: *American Journal of Community Psychology* 41.1-2 (Mar. 2008). Read, pp. 127–150. issn: 1573-2770. doi: 10.1007/s10464-007-9156-6.

[4] P. Olsson, L. H. Gunderson, S. R. Carpenter, P. Ryan, L. Lebel, C. Folke, and C. S. Holling. “Shooting the rapids: navigating transitions to adaptive governance of social-ecological systems”. In: *Ecology and society* 11.1 (2006).

[5] T. Comes. “Designing for Networked Community Resilience”. In: *Procedia Engineering*. Humanitarian Technology: Science, Systems and Global Impact 2016, HumTech2016 159.Supplement C (Jan. 2016), pp. 6–11. issn: 1877-7058. doi: 10.1016/j.proeng.2016.08.057.

[6] P. R. Lawrence and J. W. Lorsch. *Organization and environment managing differentiation and integration*. 1967.

[7] R. B. Duncan. “Characteristics of organizational environments and perceived environmental uncertainty”. In: *Administrative science quarterly* (1972), pp. 313–327.

[8] T. W. Malone, R. Laubacher, and C. Dellarocas. “The collective intelligence genome”. In: *MIT Sloan management review* (2010).

[9] T. W. Malone. *Superminds: The surprising power of people and computers thinking together*. Little, Brown Spark, 2018.

[10] M. Galesic, D. Barkoczi, A. M. Berdahl, D. Biro, G. Carbone, I. Giannoccaro, R. L. Goldstone, C. Gonzalez, A. Kandler, A. B. Kao, *et al.* “Beyond collective intelligence: Collective adaptation”. In: *Journal of the Royal Society interface* 20.200 (2023), p. 20220736.

[11] A. W. Woolley, I. Aggarwal, and T. W. Malone. “Collective intelligence in teams and organizations”. In: *Handbook of collective intelligence* (2015), pp. 143–168.

1

[12] F. Heylighen. “Self-organization in Communicating Groups: The Emergence of Coordination, Shared References and Collective Intelligence”. en. In: *Complexity Perspectives on Language, Communication and Society*. Ed. by À. Massip-Bonet and A. Bastardas-Boada. Berlin, Heidelberg: Springer, 2013, pp. 117–149. isbn: 978-3-642-32817-6. doi: 10.1007/978-3-642-32817-6_10.

[13] L. Argote. “Input uncertainty and organizational coordination in hospital emergency units”. In: *Administrative science quarterly* (1982), pp. 420–434.

[14] T. W. Malone and K. Crowston. “The Interdisciplinary Study of Coordination”. In: *ACM Comput. Surv.* 26.1 (Mar. 1994), pp. 87–119. issn: 0360-0300. doi: 10.1145/174666.174668.

[15] J. Whittaker, B. McLennan, and J. Handmer. “A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges”. In: *IJDRR* 13 (Sept. 2015), pp. 358–368. issn: 2212-4209. doi: 10.1016/j.ijdrr.2015.07.010.

[16] L. K. Comfort. “Crisis management in hindsight: Cognition, communication, coordination, and control”. In: *Public administration review* 67 (2007), pp. 189–197.

[17] J. Wolbers, K. Boersma, and P. Groenewegen. “Introducing a fragmentation perspective on coordination in crisis management”. In: *Organization Studies* 39.11 (2018), pp. 1521–1546.

[18] K. Haynes, D. K. Bird, and J. Whittaker. “Working outside ‘the rules’: Opportunities and challenges of community participation in risk reduction”. en. In: *IJDRR* 44 (Apr. 2020), p. 101396. issn: 2212-4209. doi: 10.1016/j.ijdrr.2019.101396.

[19] V. Grimm, E. Revilla, U. Berger, F. Jeltsch, W. M. Mooij, S. F. Railsback, H.-H. Thulke, J. Weiner, T. Wiegand, and D. L. DeAngelis. “Pattern-oriented modeling of agent-based complex systems: lessons from ecology”. In: *science* 310.5750 (2005), pp. 987–991.

[20] C. W. Reynolds. “Flocks, herds and schools: A distributed behavioral model”. In: *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*. 1987, pp. 25–34.

[21] J. R. Galbraith. *Designing organizations: Strategy, structure, and process at the business unit and enterprise levels*. John Wiley & Sons, 2014.

[22] L. Backstrom, D. Huttenlocher, J. Kleinberg, and X. Lan. “Group formation in large social networks: membership, growth, and evolution”. In: *Proceedings of the 12th ACM SIGKDD international conference on Knowledge discovery and data mining*. 2006, pp. 44–54.

[23] R. J. Foti and N. Hauenstein. “Pattern and variable approaches in leadership emergence and effectiveness.” In: *Journal of Applied Psychology* 92.2 (2007), p. 347.

[24] N. Levina and E. Vaast. “The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems”. In: *MIS quarterly* (2005), pp. 335–363.

[25] R. R. Dynes and B. Aguirre. “Organizational Adaptation To Crises: Mechanisms Of Coordination And Structural Change”. en. In: *Disasters* 3.1 (Mar. 1979), pp. 71–74. issn: 03613666. doi: 10.1111/j.1467-7717.1979.tb00200.x.

[26] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. en. In: *Disasters* 38.s1 (Apr. 2014), S50–S72. issn: 1467-7717. doi: 10.1111/disa.12052.

[27] S. A. Kauffman. *The Origins of Order: Self-organization and Selection in Evolution*. en. Oxford University Press, 1993. isbn: 978-0-19-507951-7.

[28] L. K. Comfort. “Self-Organization in Complex Systems”. In: *Journal of Public Administration Research and Theory: J-PART* 4.3 (1994), pp. 393–410. issn: 1053-1858.

[29] D. Anzola, P. Barbrook-Johnson, and J. I. Cano. “Self-organization and social science”. In: *Computational and Mathematical Organization Theory* 23.2 (2017), pp. 221–257.

[30] T. Comes, B. Van de Walle, and L. Van Wassenhove. “The coordination-information bubble in humanitarian response: theoretical foundations and empirical investigations”. In: *Production and Operations Management* 29.11 (2020), pp. 2484–2507.

[31] L. Palen, K. M. Anderson, G. Mark, J. Martin, D. Sicker, M. Palmer, and D. Grunwald. “A Vision for Technology-mediated Support for Public Participation & Assistance in Mass Emergencies & Disasters”. In: *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference*. ACM-BCS ’10. Swinton, UK, UK: British Computer Society, 2010, 8:1–8:12. isbn: 978-1-4503-0192-3.

[32] M. Turoff, M. Chumer, B. V. d. Walle, and X. Yao. “DERMIS: The Design of a Dynamic Emergency Response Management Information System”. English. In: *JITTA : Journal of Information Technology Theory and Application; Hong Kong* 5.4 (2004), pp. 1–35. issn: 15324516.

[33] A. Abbasi and N. Kapucu. “Structural dynamics of organizations during the evolution of interorganizational networks in disaster response”. In: *Journal of Homeland Security and Emergency Management* 9.1 (2012).

[34] J. K. Schakel and J. Wolbers. “To the edge and beyond: how fast-response organizations adapt in rapidly changing crisis situations”. In: *human relations* 74.3 (2021), pp. 405–436.

[35] N. Bharosa. “Netcentric information orchestration: assuring information and system quality in public safety networks.” en. OCLC: 840441830. PhD thesis. Oisterwijk: BOXPress, 2011.

1

[36] T. Comes, O. Vybornova, and B. Van de Walle. “Bringing Structure to the Disaster Data Typhoon: An Analysis of Decision-Makers’ Information Needs in the Response to Haiyan”. In: *2015 AAAI Spring Symposium Series*. 2015.

[37] H. Baharmand, T. Comes, and M. Lauras. “Supporting group decision makers to locate temporary relief distribution centres after sudden-onset disasters: A case study of the 2015 Nepal earthquake”. In: *IJDRR* 45 (2020). Publisher: Elsevier, p. 101455.

[38] T. Comes. “Cognitive biases in humanitarian sensemaking and decision-making lessons from field research”. In: *2016 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*. Mar. 2016, pp. 56–62. doi: 10.1109/COGSIMA.2016.7497786.

[39] B. Van de Walle, B. Brugghemans, and T. Comes. “Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination”. In: *IJHCS* 95 (Nov. 2016), pp. 66–79. issn: 1071-5819. doi: 10.1016/j.ijhcs.2016.05.001.

[40] B. Van de Walle, B. Brugghemans, and T. Comes. “Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination”. In: *IJHCS* 95 (2016), pp. 66–79.

[41] N. Bharosa, J. Lee, and M. Janssen. “Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises”. en. In: *Information Systems Frontiers* 12.1 (Mar. 2010), pp. 49–65. issn: 1387-3326, 1572-9419. doi: 10.1007/s10796-009-9174-z.

[42] J. A. Marrone. “Team boundary spanning: A multilevel review of past research and proposals for the future”. In: *Journal of management* 36.4 (2010), pp. 911–940.

[43] S. L. Star and J. R. Griesemer. “Institutional ecology,translations’ and boundary objects: Amateurs and professionals in Berkeley’s Museum of Vertebrate Zoology, 1907-39”. In: *Social studies of science* 19.3 (1989), pp. 387–420.

[44] Y. Tim, S. L. Pan, S. Bahri, and A. Fauzi. “Digitally enabled crime-fighting communities: Harnessing the boundary spanning competence of social media for civic engagement”. In: *Information & Management* 54.2 (2017), pp. 177–188. issn: 0378-7206. doi: https://doi.org/10.1016/j.im.2016.05.006.

[45] N. Bharosa, M. Janssen, and Y.-H. Tan. “A research agenda for information quality assurance in public safety networks: information orchestration as the middle ground between hierarchical and netcentric approaches”. In: *Cognition, Technology & Work* 13.3 (2011), pp. 203–216.

[46] J. A. Marrone, P. E. Tesluk, and J. B. Carson. “A multilevel investigation of antecedents and consequences of team member boundary-spanning behavior”. In: *Academy of Management Journal* 50.6 (2007), pp. 1423–1439.

[47] A. Zagorecki, K. Ko, and L. K. Comfort. "Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments". In: *JASSS* 13.3 (2009), p. 3. issn: 1460-7425.

[48] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. "Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats". In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

[49] P. Tubaro and A. A. Casilli. ""An Ethnographic Seduction": How Qualitative Research and Agent-based Models can Benefit Each Other". In: *Bulletin of Sociological Methodology/Bulletin de Méthodologie Sociologique* 106.1 (2010), pp. 59–74.

[50] S. Bharwani. "Adaptive knowledge dynamics and emergent artificial societies: ethnographically based multi-agent simulations of behavioural adaptation in agro-climatic systems". In: *University of Kent, UK* (2004).

[51] S. Bharwani, M`. Coll Besa, R. Taylor, M. Fischer, T. Devisscher, and C. Kenfack. "Identifying Salient Drivers of Livelihood Decision-Making in the Forest Communities of Cameroon: Adding Value to Social Simulation Models". In: *JASSS* 18.1 (2015), p. 3. issn: 1460-7425.

[52] A. Ghorbani, G. Dijkema, and N. Schrauwen. "Structuring Qualitative Data for Agent-Based Modelling". In: *JASSS* 18.1 (2015), p. 2. issn: 1460-7425.

[53] B. Castellani, P. Barbrook-Johnson, and C. Schimpf. "Case-based methods and agent-based modelling: bridging the divide to leverage their combined strengths". In: *IJSRM* 22.4 (2019), pp. 403–416.

[54] J. W. Creswell and J. D. Creswell. *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications, 2017.

[55] R. K. Yin. *Case Study Research: Design and Methods*. en. Google-Books-ID: FzawIAdilHkC. SAGE, 2014. isbn: 978-1-4129-6099-1.

[56] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. "Different Modelling Purposes". In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[57] I. Koskinen, J. Zimmerman, T. Binder, J. Redstrom, and S. Wensveen. *Design research through practice: From the lab, field, and showroom*. Elsevier, 2011.

[58] P. J. Stappers and E. Giaccardi. "Research through design". In: *The encyclopedia of human-computer interaction*. The Interaction Design Foundation, 2017, pp. 1–94.

[59] P. J. Stappers. "Doing design as a part of doing research". In: *Design research now*. Springer, 2007, pp. 81–91.

[60] J. Zimmerman, J. Forlizzi, and S. Evenson. “Research through design as a method for interaction design research in HCI”. In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007, pp. 493–502.

[61] V. Nespeca, K. Meester, T. Comes, L. Piccolo, G. Burel, A. Aker, and D. Maynard. *Results of second COMRADES platform evaluation*. en. Deliverable of the COMRADES EU project D 2.4. Delft University of Technology, 2018.

[62] V. Nespeca, K. Meester, L. Piccolo, A. Aker, G. Burel, T. Comes, and D. Maynard. *Results of third COMRADES platform evaluation*. en. Deliverable of the COMRADES EU project D 2.5. Delft University of Technology, 2018.

2

Actor-centred Disaster Information Sharing: An analysis of the literature

This chapter provides an analysis of the current literature and is structured as follows: first, it discusses the interplay between resilience, collective intelligence, coordinated self-organisation, and information in the volatile environment of disasters, stressing the need for an actor-centred perspective to better understand this interplay. Second, considering the promise of combining ABM and qualitative case study research to study ACDIS, it reviews existing ABMs focused on this topic as well as methodologies for developing ABMs based on qualitative case study research. The chapter concludes with a review of informational boundary spanning and its role in fostering disaster information sharing. Throughout the chapter, the knowledge gaps associated with each of the research questions posed in the introduction (RQ1 to RQ4) are illustrated and motivated based on existing literature.

2.1. Disaster resilience through actor-centred information sharing

This section discusses literature in the field of disaster resilience, focusing on disaster response, and highlights the connection between disaster resilience, collective intelligence, and coordination. It emphasizes the need for coordinated self-organisation, which relies on the effective exchange of information among organisations and groups involved in disaster response. Additionally, it explores how an actor-centred perspective can support the study of disaster information that facilitates coordinated self-organisation, thereby fostering collective intelligence and resilience during disasters.

Parts of this chapter are based on: [1–3].

2.1.1. Resilience of disaster response systems

As discussed in the introduction, the *disaster resilience* of a system depends to the ability of the actors (i.e., individual persons) and their groups within the system to collaboratively take action, self-organize, respond, and adapt to minimize the impact of crises such as disasters [4, 5].

Disaster resilience is characterized by three attributes or capacities of a system: absorption, adaptation, and transformation [6, 7]. Absorption is related to the ability to withstand shocks and quickly recover, returning to the previous state of the system before the shock occurred [8, 9]. Adaptation focuses on the system's ability to gradually and incrementally learn from and adjust in response to external shocks, reaching a new system state or maintaining the same state despite the occurrence of shocks and their uncertainty [7, 10, 11]. Transformation refers to the ability to transition into a radically new system's configuration when the current one is no-longer viable or difficult to change incrementally [7, 10]. While absorption typically refers to the short-term behaviour of a system in response to a disaster, adaptation and transformation are often associated with longer-term processes of change towards different and potentially more resilient states. However, in the context of disaster response, adaptation is also crucial in the short term to continually adjust to the volatile environment that characterizes disaster scenarios [12, 13]. This volatility involves rapid and unpredictable changes in the environment, i.e., in the factors that must be considered when individuals within a group make decisions, subsequently impacting the group's ability to achieve its objectives [14, 15].

This thesis focuses on fostering disaster resilience in the short term by enhancing the ability of a system to absorb and adapt to shocks *during the response to disasters that unfold rapidly* such as floods, earthquakes and landslides. It focuses on the resilience of *disaster response systems*, comprising (a) two main *groups*, i.e., professional response organisations and communities affected by and responding to disasters, and (b) the members of these groups, named *actors*. The actors and groups in these systems change continually due to the constant influx of new actors (e.g., due to the high turnover in humanitarian organisations), the introduction of new groups such as NGOs, and the spontaneous formation of community volunteer groups joining the response both from within or outside the system [16–18].

2.1.2. Collective intelligence and coordination for resilience

To achieve resilience by fostering absorption and adaptation during disasters, the actors and groups in a disaster response system need to work together effectively, i.e. in a collectively intelligence manner. *Collective intelligence* represents the ability of a system (composed of multiple individuals or actors) to 'act in ways that seem intelligent' [19–21]. Such intelligence, in its most general sense, entails the system's ability to solve a wide variety of complex problems in a broad range of environments [22].

To study if a system is characterized by collective intelligence it is necessary to

(a) choose a system that is composed of multiple individuals carrying out activities that are at least to some extent interconnected (i.e., they present dependencies Cf. Section 1.1), and (b) to consider a particular problem to be addressed or goal to be achieved by the system [22]. According to this perspective, collective intelligence is observer-dependent, as it is influenced by the system considered and by the problem and performance indicators used to evaluate the system's success in addressing the problem.

In this thesis, the systems observed are disaster response systems consisting of professional response organisations and communities affected by a disaster or responding to a disaster, and by actors belonging to these groups (Cf. Section 2.1.1). The activities carried out by these actors are interconnected, as they must allocate their resources to meet the needs of locally affected communities in the most effective way, all while sharing access to limited (and possibly damaged) transportation and communication infrastructure. Complex problems that need to be addressed by these systems are those that arise from the occurrence of disruptive events or more generally by the occurrence of frequent and unpredictable environmental changes associated with disasters, requiring the system to absorb and adapt to such events in order to be resilient.

A system characterized by collective intelligence draws from a number of capabilities including *sensing* (or observing) by detecting and making sense of information regarding relevant environmental changes in a timely manner, *remembering* information and knowledge by preserving it and transferring it from where it is available to where it is needed for coordination and decision making, and *learning* by recognizing and memorizing knowledge such as best practices including who is most effective at carrying out particular roles and adapt accordingly [22–24].

Further, a system's collective intelligence relies on its ability to *coordinate* the activities of the individuals in the system and jointly manage resources (e.g., human resources, physical supplies, information, and knowledge) to address specific problems. This coordination is particularly challenging in disaster response systems due to the heterogeneous objectives, capabilities, and communication channels of the board range organisations and groups operating in disaster response, which typically do not work together and, in some cases, may be working together for the first time [12, 25–28]. Additionally, the constant influx of new actors and groups (Cf. 2.1.1) makes it difficult to establish mutual trust and standards for collaboration before disasters strike, both of which are crucial to support coordination [12, 16–18, 28–31]. This makes coordination in disaster response systems even more challenging.

2.1.3. Coordinated self-organisation is required

To be resilient, a system must adapt to the volatility of disaster response environments characterized by continually, rapidly, and unexpectedly changing conditions [12, 16, 32]. This adaptation often occurs through *self-organisation*, which does not result from top-down decisions but rather from the networked interactions and mutual adjustments of different actors. These interactions can lead to the spontaneous emergence of order in the form of organisational patterns consisting of e.g., new groups, shifts in organisational structures (such as new roles), and changes in information flows [9, 12, 17, 25, 28, 33–36].

While self-organisation can enhance a system's ability to adapt to a volatile environment in a decentralized and flexible manner, it also poses coordination challenges. More specifically, self-organisation can lead to the emergence of fragmented pockets of coordination (or, 'coordination-information bubbles') that grow increasingly stable and difficult to bridge over time [36]. This fragmentation can enhance coordination in routine disaster operations [37]. However, it poses significant challenges in non-routine operations, where mutual adjustments between actors and groups are essential, as is typically the case during disaster response [26]. In such contexts, fragmentation disrupts communication between groups, impairs collective sense-making, and prevents the development of a 'common operating picture,' which is vital for effective coordination and collective intelligence [12, 27, 38]. As such, to foster the resilience of disaster response systems, it is crucial to support both self-organisation and the ability to adapt from the bottom up, as well as the capability to avoid fragmentation and maintain coordination among different groups while they are adapting. In this dissertation, a system's ability to support both coordination and self-organisation in disaster response is defined as coordinated self-organisation.

Fragmentation in disaster response systems often occurs between professional response organisations and communities, despite both groups having access to mutually relevant information and needing to collaborate effectively to ensure resilience (cf. Section 2.1.1) [17, 39, 40]. This thesis focuses on ensuring coordinated self-organisation of communities and professional response organisations.

2.1.4. Actor-centred disaster information sharing

To support coordinated self-organisation and collective intelligence it is crucial to facilitate effective information sharing across the multiple actors and their groups operating in disaster response systems. First, information sharing contributes to the actors' ability to detect relevant environmental changes that require adaptation [12]. Second, through information sharing, actors and their groups continually learn who is doing what, where, when, and how well, enabling them to work together effectively by adapting their organisational structures and roles and mutually adjusting their activities [17, 25]. Third, effective information sharing prevents the formation of fragmented networks and pockets of coordination across which it becomes increasingly challenging over time to share information and cooperate [36]. Finally, information sharing also enables actors to reinstate predefined boundaries and divisions of roles (thus limiting self-organisation) to support the coordination of routine tasks [37].

In this context, the challenge for disaster information sharing is the volatility of the groups, actors belonging to the groups, and of the actor's roles as responsibilities [26, 35]. When continual changes occur in the actors and groups participating in disaster response (Cf. Section 2.1.1) and in their organisational structures (including the roles assumed by the group's members) due to self-organisation, both the information needed and the actors who need it tend to shift rapidly. As such, information flows must continuously adapt to provide the information needed to the actors who need it and thus support coordinated self-organisation. Yet, recent case studies on disasters show that supporting coordination and self-organisation via information remains challenging [41, 42]. 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 [43, 44]. As a result, the quality of information exchanged among the actors and groups operating in disaster response systems remains poor, characterized often by a lack of relevance, timeliness, accessibility, reliability, and verifiability [27, 28, 45–47]. This is for example the case for disaster information sharing between professional response organisations and communities [17, 40, 48]. In sum, fostering disaster information sharing that supports coordinated self-organisation remains a challenge.

One promising approach to address this challenge is to identify and leverage mechanisms that foster the emergence of effective inter-group information sharing in self-organizing disaster response systems [28, 36, 49–51]. Inter-group information sharing in disaster response systems emerges from individual information sharing behaviour at the micro level (e.g., information-sharing preferences and load). It can also arise from the complex interplay of micro-level behaviour with intra-group information sharing practices at the meso level, as well as with inter-group information sharing practices and environmental conditions (e.g., volatility) at the macro level [17, 27, 39, 52]. To explore how coordinated self-organisation can be supported through the emergence of effective inter-group information sharing in disaster contexts, it is essential to adopt a perspective that considers micro-level factors and their potential interplay with meso- and macro-level factors. This dissertation refers to this perspective as actor-centred (termed ACDIS, Cf. Sec 1.3), particularly focusing on the role of micro-level behaviour on shaping intergroup information sharing during disasters.

Several studies have demonstrated the potential of analysing disaster information sharing from an actor-centred perspective [27, 28, 44, 47, 51, 53–55]. However, to systematically study how information sharing can support coordinated self-organisation from this perspective, it is crucial to understand its characteristics and the requirements for evaluating it, including key performance indicators (KPIs) for assessing its performance. Yet, a conceptual framework that captures these characteristics and requirements is missing, thus impairing the systematic study of disaster information sharing from an actor-centred perspective. This knowledge gap is addressed by answering the RQ1 posed in the introduction of this thesis.

2.2. Agent-based modelling of actor-centred disaster information sharing

Modelling and simulation can support the study of inter-group information sharing e.g., by providing the means to explore the implications of different information sharing practices and behaviours [51, 53, 55–57]. Among the available modelling paradigms, Agent-Based Modelling (ABMs) is particularly suited for studying actor-centred information sharing across multiple groups given its ability to capture and investigate the implications of complex interactions across multiple levels of analysis (e.g., micro, meso, and macro) and their impact on system's behaviour for a given phenomenon of interest [32, 58, 59]. The currently available actor-centred ABMs of disaster information sharing are reviewed in the following.

2.2.1. Actor-centred ABMs of inter-group disaster information sharing

To qualify as an ABM of ACDIS, a model must represent individual actors as agents and account for the effects of their information-sharing behaviour at the micro level on intergroup information exchange. While it may also incorporate interactions between micro, meso (groups), and macro (networks of groups) levels in shaping information exchange, this is not a requirement for the model to qualify as ACDIS.

Furthermore, since fragmentation and lack of information exchange in disaster response systems are particularly pronounced between communities and professional responders, this dissertation focuses on studying the exchange of information between these two groups (cf. Sections 2.1.3 and 2.1.4). To address this, an actor-centred agent-based model (ABM) of disaster information exchange between professional response organisations and communities is necessary to explore disaster information sharing in the context of this thesis.

Several ABMs have been proposed for disaster information sharing. Some are centred at the group (meso) level, meaning that each agent represents a group [54, 60]. These models focus on capturing inter-group information exchange, without however considering the micro level behaviour of actors. As such, these models are not actor centred. Other models assume that agents are individual actors, with their individual behaviour at the micro level affecting information exchange within groups [61]. Such models are not actor centred, as they do not consider the impact of individual behaviour on inter-group information exchange. The remaining ABMs are actor centred they study the implications of individual (micro-level) behaviour on inter-group information exchange [51, 55, 62]. However, most of these latter category of models consider information exchange among professional response organisations, without involving communities. Only [55] accounts for information exchange between informal groups (communities) and professional response organisations, focusing primarily on one-way communication from professional response organisations to communities. This analysis of existing ABMs of disaster information exchange across groups from an actor-centred perspective is summarized in table 2.1.

In sum, an ABM is missing that embraces an actor-centred perspective and enables the study of the interplay between the micro, meso, and macro levels while considering two-way communication between professional response organisations and communities. This knowledge gap is represented by RQ2, as shown in the introduction of this thesis. The next section reviews methodologies for developing

Category of ABM study	Actor level (micro)	Intra-group information sharing	Inter-group information sharing	Communities <—> Professionals?
Group-centred [54, 60]	Not considered	Not considered: 1 agent = 1 group	Info. exchange among agents	Not considered
centred on individual actor with intra-group info exchange [61]	Considers individual behaviour (1 agent = 1 actor).	Info. exchange among agents	Not considered: only one group in the model	Not considered
Actor-centred [51, 55, 62]	Considers individual behaviour (1 agent = 1 actor)	Info. exchange among agents	Info. exchange among agents belonging to different groups	Considered only in [55], but one-way professionals –> communities

Table 2.1: Categories of existing ABMs of disaster information sharing, focusing on whether they consider the micro level, intra-group information exchange, inter-group information exchange, the and the extent to which they account for two-way communication ("<—>") between informal response groups (communities) and mandated response organisations (professionals).

ABMs of ACDIS.

2.2.2. Methodologies for Developing actor-centred ABMs of disaster information sharing

Building empirical ABMs of a phenomenon of interest such as ACDIS is typically data-intensive given the high level of detail captured in these models (especially at the micro or individual level). Quantitative data on information exchange during disasters is typically lacking given the practical and ethical concerns related to interfering with current operations, privacy associated with informal information exchange, and the challenge of aligning pre-planned research activities with unexpectedly occurring disasters. As such, using quantitative methods such as surveys becomes challenging. Crisis simulation experiments can be an effective tool to collect such information in a controlled setting [27, 44], but their high costs also limits the number of experiments that can be run. As an alternative or in addition to experiments, qualitative research applied to case studies of previously occurred disasters is a powerful means to capture information exchange in disasters from an actor-centred perspective [63, 64]. A qualitative approach is also useful for new phenomena, such as ACDIS, where the existing body of knowledge is insufficient to formulate hypotheses. In such situations, an exploratory approach is required, for which qualitative research is particularly well-suited [65]. However, although there are different methodologies to develop ABMs based on qualitative research [66–68], a rigorous methodology is missing that enables to strike a balance between the *comparability* across cases provided by methodologies that rely on a common and context-independent framework (e.g., [66]) and the *flexibility* to study any policy problem provided by methodologies that focus on capturing a case study without relying on a common framework (e.g., [68]).

Additionally, the study of ACDIS processes using ABMs may require developing and utilizing a range of models with varying purposes, from theoretical to empirical [69]. Theoretical models are useful, for example, in aiding the formulation hypotheses about the effects of specific mechanisms, which can later be tested in empirical settings [51, 53, 57, 70]. In contrast, empirical models can describe existing knowledge relevant to a specific case or phenomenon [55], assess whether particular mechanisms, such as bounded rationality, account for observed system behaviours, as in [64], and explore the potential impacts of policies before their implementation [71, 72]. However, there is a lack of a versatile methodology that supports the development of ABMs tailored for both theoretical and empirical investigations of the same phenomenon of interest.

In sum, a rigorous methodology is missing for developing ABMs of a phenomenon of interest (in this case, ACDIS) through qualitative case study research that balances comparability and flexibility while providing versatility. This knowledge gap is addressed by answering RQ2, as outlined in the introduction of this thesis.

2.3. Actor-centred disaster information sharing through boundary spanning

Supporting coordinated self-organisation relies of the effective exchange of information among actors belonging to different groups (Cf. Section 2.1.4). Some actors are more effective than others at facilitating inter-group information exchange, eventually becoming Informational Boundary Spanners (IBSs), i.e., key hubs for information exchange across different groups [47, 51, 54, 73–79]. Levina and Vaast [80] found that granting the formal mandate to perform the IBS role does not guarantee that the selected actor will effectively function as an hub for inter-group information exchange. Rather, IBSs who effectively convey information across groups emerge through mechanisms resulting from dynamic interactions among individuals belonging to the different groups [80]. More specifically, IBSs emergence depends on mechanisms resulting from the complex interplay between different factors and processes at the micro (individual group member), meso (group), and macro level (network of groups) [77, 80]. Understanding these mechanism from an actor-centred perspective is key to foster the emergence of IBSs and thus support inter-group information exchange and coordinated self-organisation (Cf. Section 2.1.4). However, these mechanisms are still poorly understood in the context of disasters which are characterized by high levels of environmental volatility.

To address this gap, it is first essential to develop a quantitative method to measure the emergence of IBSs from an actor-centred perspective by identifying the individuals that emerge as IBSs at the micro level. This is crucial to study IBSs emergence mechanisms involving a complex interplay between the micro, meso, and macro levels. While, several quantitative methods have been proposed for measuring IBSs emergence and their success [51, 74, 77, 81–84], they focus on the level of a group or multiple groups. As such, method for measuring IBS emergence at the micro level is missing, impairing the study of this phenomenon from an actor-centred perspective.

Second, while case study research has been invaluable in studying boundary spanning [74, 77, 80, 85], agent-based modelling can work in synergy with case study research [63, 86]. However, currently existing ABMs focusing on information sharing in volatile environments either consider a predefined number of formally mandated IBSs without accounting for their emergence [70]. Or, they do not focus on the emergence of IBSs [51]. As such, an ABM framework available to systematically investigate the mechanisms behind IBS emergence from an actor-centred perspective in volatile environments in missing.

In sum, a method and ABM are lacking for measuring, studying, and understanding the emergence of IBSs under different conditions of environmental volatility. This knowledge gap is captured by RQ4, as presented in the introduction.

2.4. Conclusions

This chapter analysed current literature to motivate and illustrate the knowledge gaps associated with each of the research questions (RQ1, RQ2, RQ3, and RQ4) posed in the introduction. Specifically, it showed that a conceptual framework is required to capture the characteristics and requirements of ACDIS, thus enabling its study (RQ1). Further, the chapter suggested the need for ABMs of ACDIS (RQ2), and for a rigorous methodology for developing such ABMs based on qualitative case study research (RQ3). This methodology should balance cross-case comparability and flexibility to capture different cases and provide versatility to develop ABMs with different modelling purposes. Finally, the chapter highlighted the emergence of informational boundary spanning as way to foster disaster information sharing. It introduced the need for a method to measure the emergence of IBSs from an actor-centred perspective, along with an ABM to study and understand this emergence through the method (RQ4).

The next chapter of this thesis focuses on designing a methodology to develop the conceptual framework and ABMs of ACDIS.

REFERENCES

[1] V. Nespeca, T. Comes, K. Meesters, and F. Brazier. “Towards Coordinated Self-organization: An actor-centered framework for the design of Disaster Management Information Systems”. In: *IJDRR* 51 (2020), p. 101887. issn: 2212-4209. doi: 10.1016/j.ijdrr.2020.101887.

[2] V. Nespeca, T. Comes, and F. Brazier. “A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry”. In: *JASSS* 26.1 (2023), p. 10. issn: 1460-7425. doi: 10.18564/jasss.5014.

[3] V. Nespeca, T. Comes, and F. Brazier. “Learning to connect in action: Measuring and understanding the emergence of boundary spanners in volatile times”. In: *arXiv preprint* (Under review). url: https://arxiv.org/abs/2405.11998.

[4] W. N. Adger, T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström. “Social-Ecological Resilience to Coastal Disasters”. en. In: *Science* 309.5737 (Aug. 2005). Publisher: American Association for the Advancement of Science Section: Special Viewpoints, pp. 1036–1039. issn: 0036-8075, 1095-9203. doi: 10.1126/science.1112122.

[5] F. H. Norris, S. P. Stevens, B. Pfefferbaum, K. F. Wyche, and R. L. Pfefferbaum. “Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness”. In: *American Journal of Community Psychology* 41.1-2 (Mar. 2008). Read, pp. 127–150. issn: 1573-2770. doi: 10.1007/s10464-007-9156-6.

[6] B. Walker, C. S. Holling, S. R. Carpenter, and A. Kinzig. “Resilience, adaptability and transformability in social–ecological systems”. In: *Ecology and society* 9.2 (2004).

[7] C. Folke, S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. “Resilience thinking: integrating resilience, adaptability and transformability”. In: *Ecology and society* 15.4 (2010).

[8] E. Hollnagel, D. D. Woods, and N. Leveson. *Resilience engineering: Concepts and precepts*. Ashgate Publishing, Ltd., 2006.

[9] R. J. Klein, R. J. Nicholls, and F. Thomalla. “Resilience to natural hazards: How useful is this concept?” In: *Global environmental change part B: environmental hazards* 5.1 (2003), pp. 35–45.

[10] R. W. Kates, W. R. Travis, and T. J. Wilbanks. “Transformational adaptation when incremental adaptations to climate change are insufficient”. In: *Proceedings of the National Academy of Sciences* 109.19 (2012), pp. 7156–7161.

[11] R. M. Wise, I. Fazey, M. S. Smith, S. E. Park, H. C. Eakin, E. A. Van Garderen, and B. Campbell. “Reconceptualising adaptation to climate change as part of pathways of change and response”. In: *Global environmental change* 28 (2014), pp. 325–336.

[12] L. K. Comfort. “Crisis management in hindsight: Cognition, communication, coordination, and control”. In: *Public administration review* 67 (2007), pp. 189–197.

[13] T. Comes, M. Warnier, W. Feil, and B. Van de Walle. “Critical airport infrastructure disaster resilience: A framework and simulation model for rapid adaptation”. In: *Journal of Management in Engineering* 36.5 (2020), p. 04020059.

[14] P. R. Lawrence and J. W. Lorsch. *Organization and environment managing differentiation and integration*. 1967.

[15] R. B. Duncan. “Characteristics of organizational environments and perceived environmental uncertainty”. In: *Administrative science quarterly* (1972), pp. 313–327.

[16] R. R. Dynes and B. Aguirre. “Organizational Adaptation To Crises: Mechanisms Of Coordination And Structural Change”. en. In: *Disasters* 3.1 (Mar. 1979), pp. 71–74. issn: 03613666. doi: 10.1111/j.1467-7717.1979.tb00200.x.

[17] J. Whittaker, B. McLennan, and J. Handmer. “A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges”. In: *IJDRR* 13 (Sept. 2015), pp. 358–368. issn: 2212-4209. doi: 10.1016/j.ijdrr.2015.07.010.

[18] T. Comes. “Designing for Networked Community Resilience”. In: *Procedia Engineering*. Humanitarian Technology: Science, Systems and Global Impact 2016, HumTech2016 159.Supplement C (Jan. 2016), pp. 6–11. issn: 1877-7058. doi: 10.1016/j.proeng.2016.08.057.

[19] A. W. Woolley, C. F. Chabris, A. Pentland, N. Hashmi, and T. W. Malone. “Evidence for a collective intelligence factor in the performance of human groups”. In: *science* 330.6004 (2010), pp. 686–688.

[20] T. W. Malone, R. Laubacher, and C. Dellarocas. “The collective intelligence genome”. In: *MIT Sloan management review* (2010).

[21] J. Flack, P. Ipeirotis, T. W. Malone, G. Mulgan, and S. E. Page. “Editorial to the Inaugural Issue of Collective Intelligence”. In: *Collective Intelligence* 1.1 (2022), p. 26339137221114179.

[22] T. W. Malone. *Superminds: The surprising power of people and computers thinking together*. Little, Brown Spark, 2018.

[23] G. Mulgan. *Big mind: How collective intelligence can change our world*. Princeton University Press, 2017.

[24] G. Mulgan. “Collective intelligence and governance: Imagining government as a shared brain”. In: *The Routledge Handbook of Collective Intelligence for Democracy and Governance*. Routledge, pp. 70–77.

[25] L. K. Comfort. “Self-Organization in Complex Systems”. In: *Journal of Public Administration Research and Theory: J-PART* 4.3 (1994), pp. 393–410. issn: 1053-1858.

[26] M. Turoff, M. Chumer, B. V. d. Walle, and X. Yao. “DERMIS: The Design of a Dynamic Emergency Response Management Information System”. English. In: *JITTA : Journal of Information Technology Theory and Application; Hong Kong* 5.4 (2004), pp. 1–35. issn: 15324516.

[27] N. Bharosa, J. Lee, and M. Janssen. “Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises”. en. In: *Information Systems Frontiers* 12.1 (Mar. 2010), pp. 49–65. issn: 1387-3326, 1572-9419. doi: 10.1007/s10796-009-9174-z.

[28] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. en. In: *Disasters* 38.s1 (Apr. 2014), S50–S72. issn: 1467-7717. doi: 10.1111/disa.12052.

[29] N. Kapucu. “Interorganizational coordination in dynamic context: Networks in emergency response management”. In: *Connections* 26.2 (2005), pp. 33–48.

[30] N. Kapucu, T. Arslan, and M. L. Collins. “Examining intergovernmental and interorganizational response to catastrophic disasters: Toward a network-centered approach”. In: *Administration & Society* 42.2 (2010), pp. 222–247.

[31] R. Dubey, A. Gunasekaran, N. Altay, S. J. Childe, and T. Papadopoulos. “Understanding employee turnover in humanitarian organizations”. In: *Industrial and Commercial Training* 48.4 (2016), pp. 208–214.

[32] D. Anzola, P. Barbrook-Johnson, and J. I. Cano. “Self-organization and social science”. In: *Computational and Mathematical Organization Theory* 23.2 (2017), pp. 221–257.

[33] R. A. Stallings and E. L. Quarantelli. “Emergent citizen groups and emergency management”. In: *Public administration review* 45 (1985), pp. 93–100.

[34] S. A. Kauffman. *The Origins of Order: Self-organization and Selection in Evolution*. en. Oxford University Press, 1993. isbn: 978-0-19-507951-7.

[35] K. Haynes, D. K. Bird, and J. Whittaker. “Working outside ‘the rules’: Opportunities and challenges of community participation in risk reduction”. en. In: *IJDRR* 44 (Apr. 2020), p. 101396. issn: 2212-4209. doi: 10.1016/j.ijdrr.2019.101396.

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[36] T. Comes, B. V. d. Walle, and L. V. Wassenhove. "The coordination-information bubble in humanitarian response: theoretical foundations and empirical investigations". en. In: *Production and Operations Management* (2020). issn: 1937-5956. doi: 10.1111/poms.13236.

[37] J. Wolbers, K. Boersma, and P. Groenewegen. "Introducing a fragmentation perspective on coordination in crisis management". In: *Organization Studies* 39.11 (2018), pp. 1521–1546.

[38] T. Comes, B. Van de Walle, and L. Van Wassenhove. "The coordination-information bubble in humanitarian response: theoretical foundations and empirical investigations". In: *Production and Operations Management* 29.11 (2020), pp. 2484–2507.

[39] L. Palen, K. M. Anderson, G. Mark, J. Martin, D. Sicker, M. Palmer, and D. Grunwald. "A Vision for Technology-mediated Support for Public Participation & Assistance in Mass Emergencies & Disasters". In: *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference*. ACM-BCS '10. Swinton, UK, UK: British Computer Society, 2010, 8:1–8:12. isbn: 978-1-4503-0192-3.

[40] S. Waldman and K. Kaminska. *Connecting emergency management organizations with digitally enabled emergent volunteering Literature review and best practices*. Tech. rep. Defence Research and Development Canada, Dec. 2015.

[41] T. Comes, O. Vybornova, and B. Van de Walle. "Bringing Structure to the Disaster Data Typhoon: An Analysis of Decision-Makers' Information Needs in the Response to Haiyan". In: *2015 AAAI Spring Symposium Series*. 2015.

[42] H. Baharmand, T. Comes, and M. Lauras. "Supporting group decision makers to locate temporary relief distribution centres after sudden-onset disasters: A case study of the 2015 Nepal earthquake". In: *IJDRR* 45 (2020). Publisher: Elsevier, p. 101455.

[43] T. Comes. "Cognitive biases in humanitarian sensemaking and decision-making lessons from field research". In: *2016 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*. Mar. 2016, pp. 56–62. doi: 10.1109/COGSIMA.2016.7497786.

[44] B. Van de Walle, B. Brugghemans, and T. Comes. "Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination". In: *IJHCS* 95 (Nov. 2016), pp. 66–79. issn: 1071-5819. doi: 10.1016/j.ijhcs.2016.05.001.

[45] B. Van de Walle, G. Van Den Eede, and W. Muhren. "Humanitarian Information Management and Systems". en. In: *Mobile Response*. Ed. by J. Löffler and M. Klann. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2009, pp. 12–21. isbn: 978-3-642-00440-7.

[46] B. Van de Walle and T. Comes. “On the Nature of Information Management in Complex and Natural Disasters”. In: *Procedia Engineering*. Humanitarian Technology: Science, Systems and Global Impact 2015, HumTech2015 107 (Jan. 2015), pp. 403–411. issn: 1877-7058. doi: 10.1016/j.proeng.2015.06.098.

[47] N. Bharosa and M. Janssen. “Principle-Based Design: A Methodology and Principles for Capitalizing Design Experiences for Information Quality Assurance”. en. In: *Journal of Homeland Security and Emergency Management* 12.3 (Jan. 2015). issn: 1547-7355, 2194-6361. doi: 10.1515/jhsem-2014-0073.

[48] T. Comes, K. Meesters, and S. Torjesen. “Making sense of crises: the implications of information asymmetries for resilience and social justice in disaster-ridden communities”. In: *Sustainable and Resilient Infrastructure* 4.3 (2019), pp. 124–136. doi: 10.1080/23789689.2017.1405653.

[49] A. Abbasi and N. Kapucu. “Structural dynamics of organizations during the evolution of interorganizational networks in disaster response”. In: *Journal of Homeland Security and Emergency Management* 9.1 (2012).

[50] L. K. Comfort. “Self-organization in complex systems”. In: *Journal of Public Administration Research and Theory: J-PART* 4.3 (1994), pp. 393–410.

[51] A. Zagorecki, K. Ko, and L. K. Comfort. “Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments”. In: *JASSS* 13.3 (2009), p. 3. issn: 1460-7425.

[52] A. Silver and L. Matthews. “The use of Facebook for information seeking, decision support, and self-organization following a significant disaster”. en. In: *Information, Communication & Society* 20.11 (Nov. 2017), pp. 1680–1697. issn: 1369-118X, 1468-4462. doi: 10.1080/1369118X.2016.1253762.

[53] L. K. Comfort, K. Ko, and A. Zagorecki. “Coordination in Rapidly Evolving Disaster Response Systems: The Role of Information”. en. In: *American Behavioral Scientist* 48.3 (Nov. 2004), pp. 295–313. issn: 0002-7642. doi: 10.1177/0002764204268987.

[54] N. Altay and R. Pal. “Information Diffusion among Agents: Implications for Humanitarian Operations”. In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[55] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. “Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats”. In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

[56] P. Fiala. “Information sharing in supply chains”. In: *Omega* 33.5 (2005), pp. 419–423.

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[57] N. Altay and R. Pal. “Information Diffusion among Agents: Implications for Humanitarian Operations”. In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[58] J. M. Epstein and R. Axtell. *Growing artificial societies: social science from the bottom up*. Brookings Institution Press, 1996.

[59] P. Antosz, T. Szczepanska, L. Bouman, J. G. Polhill, and W. Jager. “Sensemaking of causality in agent-based models”. In: *IJSRM* (2022), pp. 1–11.

[60] C. Baber, N. A. Stanton, J. Atkinson, R. McMaster, and R. J. Houghton. “Using social network analysis and agent-based modelling to explore information flow using common operational pictures for maritime search and rescue operations”. In: *Ergonomics* 56.6 (2013), pp. 889–905.

[61] L. Bateman and E. Gralla. “Evaluating Strategies for Intra-Organizational Information Management in Humanitarian Response”. en. In: *Proceedings of the 15th ISCRAM Conference*. Rochester, NY, 2018, p. 13.

[62] S. K. Aros and D. E. Gibbons. “Exploring communication media options in an inter-organizational disaster response coordination network using agent-based simulation”. In: *European Journal of Operational Research* 269.2 (2018), pp. 451–465.

[63] B. Castellani, P. Barbrook-Johnson, and C. Schimpf. “Case-based methods and agent-based modelling: bridging the divide to leverage their combined strengths”. In: *IJSRM* 22.4 (2019), pp. 403–416.

[64] C. Adam and B. Gaudou. “Modelling Human Behaviours in Disasters from Interviews: Application to Melbourne Bushfires”. In: *JASSS* 20.3 (2017), p. 12. issn: 1460-7425.

[65] J. W. Creswell and J. D. Creswell. *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications, 2017.

[66] A. Ghorbani, G. Dijkema, and N. Schrauwen. “Structuring Qualitative Data for Agent-Based Modelling”. In: *JASSS* 18.1 (2015), p. 2. issn: 1460-7425.

[67] S. Bharwani. “Adaptive knowledge dynamics and emergent artificial societies: ethnographically based multi-agent simulations of behavioural adaptation in agro-climatic systems”. In: *University of Kent, UK* (2004).

[68] S. Bharwani, M`. Coll Besa, R. Taylor, M. Fischer, T. Devisscher, and C. Kenfack. “Identifying Salient Drivers of Livelihood Decision-Making in the Forest Communities of Cameroon: Adding Value to Social Simulation Models”. In: *JASSS* 18.1 (2015), p. 3. issn: 1460-7425.

[69] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. “Different Modelling Purposes”. In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[70] J. K. Hazy and B. F. Tivnan. “The impact of boundary spanning on organizational learning: Computational explorations”. In: *Emergence* 5.4 (2003), pp. 86–123.

[71] J. Badham, P. Barbrook-Johnson, C. Caiado, and B. Castellani. “Justified stories with agent-based modelling for local COVID-19 planning”. In: *JASSS* 24.1 (2021), p. 8.

[72] B. Edmonds and L. ní Aodha. “Using Agent-Based Modelling to Inform Policy – What Could Possibly Go Wrong?” en. In: *Multi-Agent-Based Simulation XIX*. Ed. by P. Davidsson and H. Verhagen. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 1–16. isbn: 978-3-030-22270-3. doi: 10.1007/978-3-030-22270-3_1.

[73] M. L. Tushman. “Special boundary roles in the innovation process”. In: *Administrative science quarterly* (1977), pp. 587–605.

[74] D. G. Ancona and D. F. Caldwell. “Bridging the boundary: External activity and performance in organizational teams”. In: *Administrative science quarterly* (1992), pp. 634–665.

[75] N. Kapucu. “Interagency communication networks during emergencies: Boundary spanners in multiagency coordination”. In: *The American review of public administration* 36.2 (2006), pp. 207–225.

[76] R. H. Ballou. “The evolution and future of logistics and supply chain management”. In: *European business review* 19.4 (2007), pp. 332–348.

[77] J. A. Marrone. “Team boundary spanning: A multilevel review of past research and proposals for the future”. In: *Journal of management* 36.4 (2010), pp. 911–940.

[78] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. In: *Disasters* 38.s1 (2014), S50–S72.

[79] I. Van Meerkerk and J. Edelenbos. “The effects of boundary spanners on trust and performance of urban governance networks: findings from survey research on urban development projects in the Netherlands”. In: *Policy Sciences* 47 (2014), pp. 3–24.

[80] N. Levina and E. Vaast. “The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems”. In: *MIS quarterly* (2005), pp. 335–363.

[81] M. T. Hansen. “The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits”. In: *Administrative science quarterly* 44.1 (1999), pp. 82–111.

[82] J. N. Cummings. “Work groups, structural diversity, and knowledge sharing in a global organization”. In: *Management science* 50.3 (2004), pp. 352–364.

[83] J. A. Marrone, P. E. Tesluk, and J. B. Carson. “A multilevel investigation of antecedents and consequences of team member boundary-spanning behavior”. In: *Academy of Management Journal* 50.6 (2007), pp. 1423–1439.

[84] W. Van Osch, C. Steinfield, and Y. Zhao. “Towards behavioral measures of boundary spanning success: The effectiveness and efficiency of team boundary spanning in enterprise social media”. In: *Research Papers* (June 2016).

[85] H. Lifshitz-Assaf. “Dismantling knowledge boundaries at NASA: The critical role of professional identity in open innovation”. In: *Administrative science quarterly* 63.4 (2018), pp. 746–782.

[86] P. Tubaro and A. A. Casilli. ““An Ethnographic Seduction”: How Qualitative Research and Agent-based Models can Benefit Each Other”. In: *Bulletin of Sociological Methodology/Bulletin de Méthodologie Sociologique* 106.1 (2010), pp. 59–74.

3
Research methodology

Informing the development of computational models through qualitative case study research is a promising approach to study social phenomena stemming from human interactions and behaviour such as ACDIS. Yet, while there are different methodologies to develop models based on qualitative research, a methodology is missing that enables to strike a balance between the *comparability* across cases provided by methodologies that rely on a common and context-independent framework and the *flexibility* to study any phenomenon of interest provided by methodologies that focus on capturing a case study without relying on a common framework. Additionally, a rigorous methodology is missing that enables the development of both theoretical and empirical models for studying a specific phenomenon of interest. In this chapter, the authors propose a methodology targeting these gaps for ABMs in two stages. First, a novel conceptual framework centred on a particular phenomenon of interest is developed based on existing theories and qualitative insights from one or more case studies. Second, empirical or theoretical ABMs are developed based on the framework and generic models. This chapter establishes a foundation to answer RQs 1-3.

3.1. Introduction

Qualitative research is a powerful means to capture social dynamics and many studies e.g. from the social sciences provide qualitative insights on human interactions and behaviour that can support the study of phenomena involving such dynamics (e.g., ACDIS) [2–4]. Consequently, the development of Agent-Based Models (ABMs) for supporting the study of phenomena involving social dynamics can benefit greatly from integrating the results of qualitative research [5–7].

Translating nuance-rich qualitative data into a computational model is, however, challenging [8]. While the contextual richness of the data should be preserved as much as possible, distortions need to be minimized and a transparent approach is needed that ensures replicability [5, 9, 10]. Several methodologies have been proposed for integrating qualitative data into ABM by (a) using previously devel-

Parts of this chapter are based on: [1].

oped frameworks to interpret and structure data, and/or by (b) "constraining" the knowledge elicitation and analysis process through clear steps [9]. For instance, Ghorbani et al. [11] show the potential of using conceptual frameworks developed for institutional (re)design to support the design, implementation and analysis of ABMs in socio-technical systems. Further, Ghorbani et al. [12] provide an approach for structuring and interpreting qualitative data from ethnographic work on the basis of a previously developed framework (or meta-model). Conversely, Bharwani et al. suggest a mixed-methods research methodology that puts emphasis on the steps adopted to extract and validate agent rules via a participatory and ethnographic process [10, 13]. Within such a methodology, the authors rely on an exploratory phase to design a context-specific game that captures the world views and decisions of the study participants. Such a game is then used to extract agent rules.

Two gaps were identified concerning methodologies for the development of ABMs for studying a phenomenon of interest through qualitative data. Firstly, methodologies as [12] that rely on pre-existing conceptual frameworks to develop ABMs have the advantage of enabling the study of a specific phenomenon across different cases in a rigorous and consistent manner (i.e. through the same framework) which enhances the comparability of results across different cases. However, these methodologies lack in flexibility as they can only be used when an adequate framework already exists that can be applied to the phenomenon of interest. For novel phenomena such a framework may not yet be available. Further, in order to support a rigorous and systematic approach, the frameworks used in these methodologies are "pre-packaged" with particular agent architectures [11, 14] - i.e. formalized descriptions of agent theories concerning the internal processes occurring within the agents [15]. However, such a design choice reduces the flexibility of these methodologies in terms of enabling to account for different agent architectures. Other methodologies such as [10, 13] rely on specific steps to rigorously develop ABMs tailored to a given case. While such methodologies can be flexibly applied to any case without the need of a pre-existing framework, the lack of a common framework makes it difficult to ensure comparability and consistency across different cases of the same phenomenon of interest. In sum, a methodology is missing for developing ABMs for studying a phenomenon of interest that enables to maintain rigour while striking a balance between (a) comparability as the ability to retain "common ground" among different modelling studies focusing on the same phenomenon so that their results can be meaningfully juxtaposed and (b) flexibility with respect to the ability to capture novel phenomena and use different agent architectures.

Secondly, the process of studying a phenomenon of interest via ABMs may involve the development and use of a series of models with different purposes ranging from theoretical to empirical [16, 17]. Theoretical models can e.g. support the formulation of hypotheses regarding the implications of given mechanisms explaining the phenomenon of interest prior to testing them empirically [18, 19]. Conversely, empirical models can be used for instance to (a) capture a preliminary description of the currently-available knowledge that is relevant for a considered phenomenon and case [20], (b) evaluate whether particular mechanisms that are considered relevant for a given phenomenon under study actually explain its emergence (see for instance [6]), and (c) explore ex-ante the potential implications of given policies prior to their implementation [21, 22]. However, a methodology is missing that is versatile in that it enables the development of ABMs with different theoretical or empirical purposes focusing on the same phenomenon.

In this chapter, the authors propose methodology that enables to develop ABMs for studying a phenomenon of interest based on qualitative inquiry in a flexible and versatile manner. The methodology involves (i) the development of a novel conceptual framework that is centred on the considered phenomenon through one or more case studies (when such a conceptual framework in not available), and (ii) the development of empirical or theoretical ABMs guided by the application of this conceptual framework in combination with generic models. While the conceptual framework is designed to enable the identification of the agents and their interactions that are relevant for the considered phenomenon, generic models are used to guide the design of the internal processes that drive the agents' interactions found through the conceptual framework. Generic models provide a common language that can capture different agent architectures such as BDI [23] in a formalized, abstract, and reusable manner [24]. By choosing different generic models capturing different agent architectures, the modeller is provided with flexibility with respect to the choice of the way the agents and their interactions are translated into the internal rules driving the agent's interactions. The paper is structured as follows. Section 2 introduces the compositional design of ABMs through generic models. Section 3 outlines the proposed methodology, which has two phases: conceptual framework development and model development. Section 4 provides the conclusions of the chapter.

3.2. Background: Compositional development of ABMs through generic models

Brazier et al. [25] propose a compositional development method for multi-agent systems (and ABMs[1]) called DESIRE (DEsign and Specification of Interacting REasoning components). According to this method, both the agents and the system as a whole are modelled as a compositional architecture i.e. as series of interacting components that are hierarchically structured and task-based. DESIRE enables to specify both the agents' interactions (or "inter-agent functionality") and the internal processes driving such interactions (or "intra-agent functionality") in an explicit and precise manner. Further, in DESIRE the design of an ABM includes two types of knowledge, namely (a) a *process composition* concerning the tasks that the agents carry out, and (b) a *knowledge composition* capturing the knowledge structures the tasks rely on. The process composition consists of a task hierarchy (i.e. the tasks to be executed and their sub-tasks), tasks' input and output,

[1]While DESIRE was initially conceived to design multi-agent systems, it can as well be applied to the design of ABMs.

information exchange among tasks (or information links), sequencing of tasks (or task control knowledge), and task delegation (which agent carries out which tasks). Knowledge composition consist of knowledge structures that capture (a) the ontology or "information types" representing the relevant concepts the tasks rely on and (b) the knowledge bases representing the rules followed by the agents when executing tasks on the basis of the concepts. Central to the DESIRE method is the principle of compositionality, according to which the knowledge composition and process composition are captured at different levels of abstraction i.e. from abstract tasks or knowledge structures to their more and more specialized components. For instance, in the case of process composition, the abstract task "own process control" can be composed of sub-tasks (or components) such as "determine goals and commitments" and "evaluate own processes" [26].

Instead of designing an ABM from scratch every time, Brazier et al. [27] suggest that existing generic models can be re-used. Such generic models can be developed for different types of agents and agent architectures thus providing the model developer with a range of options with respect to the type of agent to be considered when designing ABMs [24]. Generic models consist of abstracted representations of the process and knowledge composition of ABMs (according to the principle of compositionality discussed above). In the case of process composition, a generic model is abstracted with respect to the tasks that the agents can carry out. These tasks can be *specialized* from the abstract categories provided in the generic model, to more specific sub-tasks that are the required for the considered ABM. Further, in the case of knowledge composition, a generic model is abstracted with respect to the knowledge structures the tasks rely on. The knowledge composition included in the generic model can be *instantiated* by (a) finding additional if, then, else statements that are nested in those captured by the knowledge bases of the generic model or (b) by providing new knowledge bases for the sub-tasks introduced in the specialization of the generic model's process composition. The knowledge composition can also be instantiated by introducing new categories in the ontology of information types accessed by the tasks.

In the seminal work by [15, 28], a weak notion of agent is introduced which is meant to capture some of the most general and widely recognized features that characterize an agent (e.g. "autonomy", or "social ability"). Brazier et al. [27] build on this weak notion of agent to design a generic model called Generic Agent Model (GAM). GAM provides a unified and formalized language which can be specialized and instantiated to capture a wide variety of agent types and architectures in a consistent, comparable and reusable manner. An overview of GAM is provided in Appendix A. Several applications of GAM have been proposed that capture different agent architectures (e.g. normative, cooperative, or BDI) [24]. These applications enabled the design of new generic models that are more specialized than GAM as they apply to specific agent architectures and classes of problems. For instance, GAM was re-used to design a new generic model called Generic Cooperative Agent Model (GCAM) that can be used to develop ABMs capturing distributed project coordination and assuming joint intentions [26].

3.3. Proposed Methodology

The methodology introduced in this chapter was developed via a research through design strategy involving a series of design iterations (Cf. Section 1.8.1). These iterations included the design of (a) a conceptual framework for ACDIS and of the methodological steps required to design it, (b) an empirical ABM for the case study of Jakarta and of the methodological steps required to develop such an ABM based on the conceptual framework and case study research, and (c) a theoretical ABM.

The resulting methodology involves two interlinked phases: conceptual framework development and model development, see Figure 3.1. In phase one, a conceptual framework capturing a specific phenomenon of interest is developed based on existing theory (literature and ABMs) and case studies. Case studies are carried out mainly through qualitative inquiry. However, quantitative data may also be collected e.g. on demographics. In phase two, a theoretical or empirical model is developed based on the conceptual framework, along with further insights from theory, empirical data from the case studies (analysed through qualitative and possibly also quantitative data analysis) if an empirical model is being developed, and generic models. Each phase is explained in detail in the following sections[2].

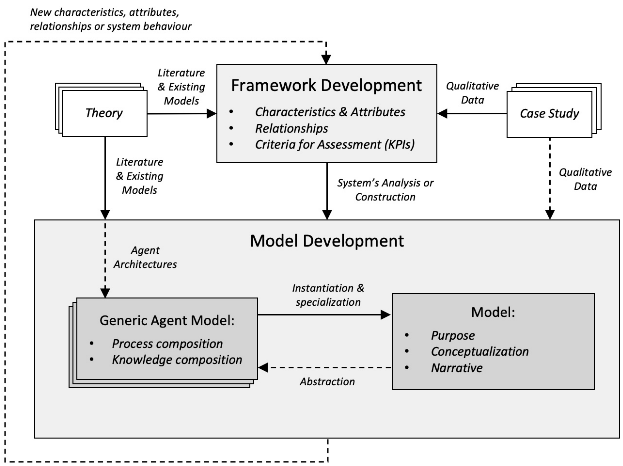

Figure 3.1: Methodology for developing agent-based models for studying a phenomenon of interest based on qualitative research. The dashed line symbolizes activities that are optional.

3.4. Phase 1: Framework Development

In this phase, existing theory and qualitative research from one or more case studies is used to design a conceptual framework centred on a particular phenomenon

[2] The explanations provided in this chapter for the first and second phases are theoretical. For practical illustrations of their application, see Chapters 4 and 5, respectively.

of interest. By such a conceptual framework the authors intend a "list" of categories of meaning and their relationships that are relevant when developing ABMs focusing on a specific phenomenon of interest. These conceptual frameworks enable part of the methodology, but they are not the methodology. Through the methodology, it is possible to develop different conceptual frameworks for different phenomenon of interests when such frameworks are not already available. In the following, firstly the composition and use of such a conceptual framework is discussed. Secondly, the suggested framework development steps are illustrated.

3.4.1. Framework use and composition

ABMs can support the study of a phenomenon of interest by enabling to simulate and systematically compare the behaviour (or performance) of a system given the system's configuration and possible alterations of this configuration [16]. Studying the results of such simulations can support the study of a phenomenon of interest by uncovering and testing mechanisms that lead to the emergence of relevant patterns in the system's behaviour or its performance. Such mechanism constitute a theory of why and how particular system's configuration lead to the emergence of given pattern of interest. Essential elements of these mechanisms are their outcomes and the contextual factors that may affect these outcomes. Given the above, the authors provide the following definitions of system's configuration, change and performance. A *system's configuration* consists of the agents, their activities and interactions with other agents and their environment that represents the context in which a phenomenon of interest is studied [7]. A system's change and performance are both related to the outcomes of the mechanisms being studied. A *system's change* refers to shifts in the configuration of a system both as a direct consequence of the agents' choice, or through emergent, self-organized and bottom-up processes generated by the agent's interactions [29–31]. A *system's performance* is intended as the extent to which a system reaches the desired behaviour. System's performance can be influenced both by the system's configuration and its change. The seminal work by [3] can provide an example of a study capturing a system's configuration, change and performance. In this case, system's performance is measured as the volume of knowledge exchanged across an organisational boundary. [3] study how such a system's performance is affected by the system's change intended as the emergence of a new organisational community (or "joint field of practice") across the organisational boundary. The emergence of such a community is facilitated by actors who adjust their role to become "boundary spanners in practice" depending on contextual factors captured in the system's configuration. Such contextual factors include the formal nomination of the actors as boundary spanners, their inclination to engage in boundary spanning activities, and their recognition as legitimate participants and negotiators on both sides of the organisational boundary.

The frameworks designed with this methodology are meant to enable to capture the key agents and their interactions that are relevant for the development of both theoretical and empirical ABMs that can support the study of the considered phenomenon of interest. Specifically, the frameworks provide the means to carry out both (a) an analysis of an existing system (e.g., a case study) by structuring qualitative data and translating it into an empirical model [12], and (b) a construction of an abstract system to be studied via a theoretical model. To this end, frameworks are required to capture a system's configuration, change, and performance.

Firstly, to capture the configuration of a system, a conceptual framework needs to provide the *system's characteristics* and their *attributes*. A system's characteristics are the fundamental components of a system (e.g. agents and their environment) that are relevant for the phenomenon of interest considered. Attributes are the features that distinguish different instances of a given characteristic. In the case of the study by [3], system's characteristics are for instance the organisations as defined by their boundaries, the actors who belong to such organisations, and their negotiation and knowledge sharing activities (interactions). Attributes of the characteristic "actor" are for example an actor's recognition as a legitimate participant and negotiator on both sides of the boundary, and his/her inclination towards participating in boundary spanning activities.

Secondly, in order to capture the system's change, a framework is required to include the *relationships* among characteristics. Such relationships represent the way the characteristics interact, possibly leading to (emergent) changes in the system's configuration. An example of relationship from the article by [3], is that between actors belonging to different organisational units who can interact via knowledge sharing activities. Through such interactions actors may develop an inclination towards boundary spanning activities, leading them to gradually assume the role of boundary spanners in practice.

Thirdly, the *criteria for assessment* are the indicators used to measure the performance of a system. In the case of [3], the criterion for assessment is the volume of knowledge exchanged across the considered organisational boundary. Figure 3.2 shows the composition and use of a conceptual framework devised to guide the development of both empirical and theoretical ABMs for studying a phenomenon of interest.

3.4.2. Framework development steps:

Developing frameworks for the design of ABMs for studying a particular phenomenon of interest requires an approach that can capture the complexity of social and socio-technical systems. Brazier et al.'s approach was chosen for developing such conceptual frameworks given it can be applied to both social and socio-technical systems [32]. Based on the chosen approach, the framework development phase follows the steps shown in figure 3.3. In the following sections, each of the steps is described in detail.

3.4.3. Literature review:

The literature and existing models (including ABMs) related to the type of system in question are studied to identify (a) the phenomenon of interest, (b) the unit of analysis for the considered phenomenon, and (c) a list of relevant characteristics

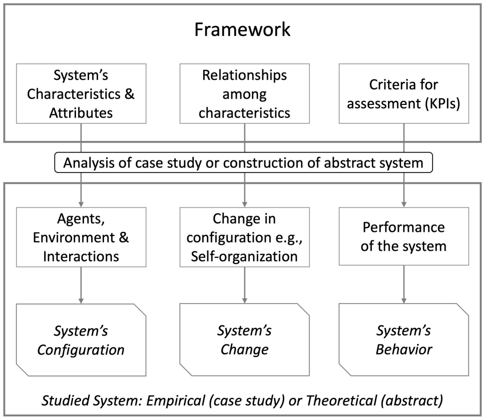

Figure 3.2: Composition (top) and use (bottom) of a conceptual framework to analyse an existing system (or case study) or construct an abstract one. Such an analysis can then inform the development of an ABM (Phase 2).

of the phenomenon of interest from the perspective of the unit of analysis. (a), (b) and (c) are only preliminary at this stage and may be refined or changed based on case study research [33].

The unit of analysis is carefully chosen to reflect the phenomenon of interest at hand. This unit refers to the micro-level entity that is going to the centre of the agent-based models the researchers intend to design. Indeed, given the generative nature of agent-based modelling [34], it is crucial that the framework

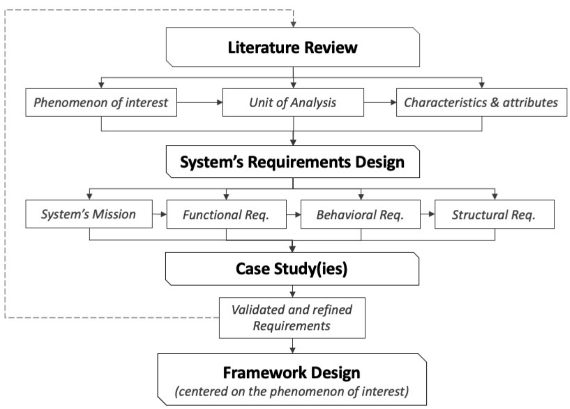

Figure 3.3: Framework development in four steps. The steps are shown in bold and their results are presented below in italics. The dashed line illustrates possible iterations through the steps.

takes the perspective of the intended model's most elementary unit. Examples of unit of analysis are a person, a household, an organisation, or an entire region.

3.4.4. Requirements design:

Brazier et al.'s approach entails the design of the system's mission and of the associated functional, behavioural and structural requirements [32]. The mission of the system is its intended purpose, that, in this case, is to address the chosen phenomenon of interest. The functional requirements are the functions that the system has to fulfil to achieve the mission. behavioural requirements define the desired system's behaviour associated with the fulfilment of the functional requirements, and the criteria for assessment that can be used for measuring the extent to which the desired behaviour is achieved. Structural requirements are the components of the system that are put in place to fulfil the behavioural requirements.

At this stage, the system's mission, and the functional, structural and behavioural requirements are designed based on the results of the previous step. Specifically, the mission is designed based on the phenomenon of interest. Then, the functional requirements are designed based on the system's characteristics and the mission. Next, the behavioural requirements are derived from the functional requirements. Finally, the structural requirements are designed based on behavioural requirements and the list of relevant systems' characteristics and attributes. This design process results in a preliminary list of requirements.

3.4.5. Case study:

In this step, the preliminary list of functional, structural, and behavioural requirements is verified and expanded based on one or more case studies [33, 35]. First, the case study is designed. This includes the selection of a case study, data collection techniques (e.g. interviews and focus groups, participant observations and archival data), and sampling strategies all of which are summarized in a data collection plan [33, 36]. The collected data is then analysed through *coding*. The way such analysis is carried out depends on the type of data collection techniques chosen [36]. However, in all cases the analysis begins with the preliminary list of requirements from the previous step.

In the case of interviews, focus groups, and participant observations the collected data is analysed with a hybrid deductive and inductive coding approach [37]. Initially, a coding schema is defined based on the preliminary list of requirements from the previous step. This list is divided in requirements and their sub-requirements. Distinctions between between these two categories are made by considering that sub-requirements offer more specific guidance on particular elements within the broader scope outlined by each requirement. For instance, if one of the requirements is 'organisation', its sub-requirements may be 'type of organisational structure', 'integration mechanisms', and 'adaptation strategies'. Next, the requirements are assigned as first-level codes in the coding schema, while the sub-requirements are designated as second-level codes. During the coding process, not only instances of the pre-defined codes are identified, but also an open (inductive) coding approach is adopted to discover new requirements and sub-requirements or to refine existing ones.

In the case of archival data or documents, the summative content analysis approach is adopted [38]. This approach is divided in two levels, namely manifest and latent. The manifest level entails finding in the archival data occurrences of the codes associated with the preliminary characteristics, attributes, relationships and criteria for assessment. At this stage, new characteristics, attributes, relationships and criteria for assessment may also be found through open coding. Next, the latent level focuses on analysing the context in which the code occurrences were found to study and revise their meaning. In the process, further instances of the codes may be found, and also new codes may be introduced. Typically, an iterative process is required between the manifest and latent levels to determine how well the meaning extrapolated from given contexts fits that associated with the codes and solve potential conflicts. When such conflicts occur, they can be addressed through an in depth inspection of their meaning, leading to a the definition of new meanings associated with the code or to new codes which reconcile the conflict. The content analysis can be considered completed when no new codes or conflicts are found in the data.

The results of this step are refined and validated behavioural and structural requirements. Further, the phenomenon of interest identified earlier may also be validated and refined together with the requirements. For instance, a new promising direction may be found from the data which may require to adjust the phenomenon of interest and align it with the new or modified requirements . Given the modifications to the requirements and phenomenon of interest, new fields of literature may be found to be relevant which were not considered in the first step. When literature confirms the finding from the case study this provides further confidence in the findings. Further, when literature is in contrast with the findings from the case study, this is an opportunity to further probe into the nature of this contrast and bring a deeper insight into both the literature and the requirements. As such, some iteration between case study research, literature review and requirements design is likely to be necessary.

3.4.6. Framework design:

The design process of the framework is based on the refined and validated requirements from the previous step. More specifically, the structural and behavioural requirements are considered. Structural requirements provide the list of the system characteristics, attributes, and relationships to be included in the framework. Each system characteristic is considered as an independent framework component, with its own attributes and relationships. When the relationships found between the system's characteristics are vertical, such as those of the type "is a part of", "can have one or more" or "contains", then the corresponding characteristics are organized hierarchically. If the relationships among the characteristics are horizontal, such as those of the type "interacts with", "causes", "performs" and "affects", these characteristics are linked with an arrow labeled with the corresponding relationship. Additionally, the behavioural requirements are used to capture the systems performance through the criteria for assessment.

3.5. Phase 2: Model Development

It is good practice to set a clear modelling purpose, as the way a model is developed, justified and also scrutinized by the scientific community depends on its purpose [17, 39]. Therefore, the model development process in this chapter takes different forms depending on the purpose of the model. More specifically, a distinction is made between models with an empirical or a theoretical purpose[3,4], affecting the way the framework and generic models are used in the development process to analyse an existing system or to construct an abstract one (cf. Section "Framework use and composition" above).

3.5.1. Model Development Steps:

Several methodologies have been proposed in the literature for developing and describing ABMs. In this chapter, the approach proposed in [41, 42] is chosen and extended to include the use of (a) the framework from the previous phase and (b) generic models such as the Generic Agent Model (GAM) [27] to guide the model development process. However, other ABM development methodologies for instance based on the ODD protocol [43] could be possibly extended in a similar manner.

The resulting approach involves the following *iterative* model development steps: Framework Application, Problem Formulation, System Identification and Composition, Model Concept Formalization, Model Narrative Development, Software Implementation, Model Evaluation, and Abstraction to Generic Model. This last step is optional. In the following sections, each step is described briefly, stressing how the framework and generic models are used to guide model development for both empirical and theoretical models. Figure 3.4 shows an overview of how the framework and generic models support the model development steps and their outcomes.

3.5.2. Framework Application:

As already mentioned in Section 3.4.1, the frameworks developed with this methodology can be applied both to construct an abstract systems to be investigated via a theoretical ABM, or to analyse an existing system so that the system's essential characteristics and attributes can be captured with an empirical ABM. The modelling purpose defines *how* the framework is applied. Specifically,

[3] *Empirical models* are those which have a direct relationships with a specific case study. Descriptions, explanations and predictions are examples of empirical modelling purposes. *Theoretical models* are those which do not have a direct relationship with any given case study or specific system. Illustrations and theoretical expositions are examples of theoretical modelling purposes. [17]

[4] With this distinction, the authors do not imply that theoretical models cannot be used in practical settings. However, theoretical model can be applied in practice only if they have been empirically tested in terms their micro assumptions and macro implications [40].

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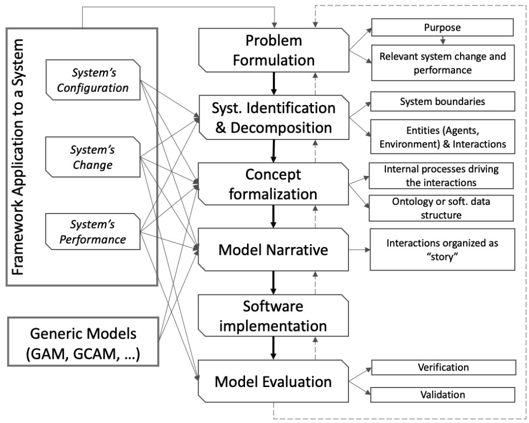

Figure 3.4: Use of the conceptual framework and generic models (left) to support the steps for the development of an Agent-Based Model (centre) with details on the result of each model development step (right). The dashed lines show possible iterations among the different steps of the model development process.

in the case of theoretical models, the framework can be used to provide an inventory of relevant system' characteristics, attributes, relationships and criteria for assessment that the researchers may want to consider in the model. With regards to empirical models, the framework provides the means to analyse the system's configuration, change and performance (see Section "Framework use and composition") that inform the following model development steps. The use of the framework application for each of the model development steps shown in Figure 3.4 are discussed in detail in the sections hereinafter.

3.5.3. Problem Formulation:

The problem formulation entails making decisions about (a) the modelling purpose and (b) the system's performance and change of interest to be captured respectively by criteria for assessment[5] and other indicators designed to study possible changes in the configuration of the system. These choices are made based on the application of the framework as shown in the following.

In the case of empirical models, the choice of a modelling purpose and of the system performance and change of interest is guided by the results of the framework application to the case study and the resulting analysis of its configuration, change, and performance. Empirical models can be employed to provide a description of the current configuration and dynamics of a given system based on the knowledge gathered through the system's analysis, literature, and existing models. While descriptive models do not aim to exactly reproduce or explain specific system's

[5] New or more detailed criteria for assessment may be introduced at this stage compared to those presented in the framework.

performance or change, they can be a first step for the development of future models aimed at studying a phenomenon of interest in the given case (see [20] as an example of description). In other cases, the analysis of system's performance uncovers that the system performs poorly or particularly well in terms of specific criteria for assessment or, that the configuration of the system changes in particular and unexpected ways. As such, the focus may be on providing explanations in terms of the mechanisms that lead to such system performance or change. The results of these explanations can inform policy formulation and evaluation (see for instance [6]). Finally, empirical models may be chosen with the purpose of exploring the implications of future policy interventions e.g. aimed at changing the configuration of the system to address the poor performance uncovered by the analysis of system's performance [21]. The choice of relevant indicators of system's performance and/or change follows from modelling purpose.

A theoretical model may be developed that abstracts from the context of the given case study to capture a range of systems [39]. In this case, the researchers can choose a modelling purpose within the broader scope of studying a phenomenon on interest. Theoretical models can, for instance, have the purpose of illustrating or exploring relationships between given system characteristics or policies and the resulting system's change or performance. The results of such modelling efforts can e.g. support the formulation of hypotheses (to be tested empirically) concerning (a) explanations for particular system's change that can be relevant for better understanding the phenomenon of interest or (b) the success of specific interventions in reaching the desired system's performance [19, 30, 44, 45]. Relevant indicators of system's change and performance are chosen on the basis of the modelling purpose. In the case of system's performance, the researcher may decide among the assessment criteria provided in the framework.

3.5.4. System Identification and Composition:

System identification involves defining the boundaries of the considered system. System composition consists of capturing the relevant system's configuration and change for the chosen modelling phenomenon of interest and modelling purpose. More specifically, the key entities (agents and the environment in which they are embedded) and their interactions to be captured in the model are defined conceptually at this stage.

In the case of empirical models, the boundaries of the system can be those of the case study to which the framework was applied. However, the considered system can be narrowed down to a specific area. The system composition is derived from the analysis of configuration and change obtained through the framework application to the identified system.

With regards to theoretical models, system identification and composition are meant to capture an abstract system, rather than a specific case study. The framework can support system composition by providing an inventory of system characteristics (e.g. key entities), attributes and relationships that are relevant for the considered phenomenon of interest and can be instanced and included in the abstract system's configuration and change.

3.5.5. Model Concept Formalization:

In this step, the system composition is formalized in a format that can be translated into software. The entities that will become agents in the model are formally defined, together with the tasks (or activities) they carry out, and their properties and state variables. Also the environment in which the agents are placed is considered as an entity characterized by tasks, properties, and states. The entities found are organized hierarchically from general classes including common properties, states, and tasks, to the entities representing the agents and environment actually considered in the model. A concept formalization can be implemented directly as a software data structure or as an ontology (which is then translated into a software data structure).

The concept formalization of a model requires capturing not only the tasks (or activities) that the agents carry out in interaction with other agents or the environment, but also the internal processes that occur within the agents that enable these interactions. While the system composition obtained at the previous step includes the key entities and their interactions that can be translated into the corresponding agents into the model, it does not provide the level of detail required to capture the agents' internal processes. To maintain a rigorous approach, another framework focused on the agents' internal processes is required to structure the implementation of a system's composition into a concept formalization. The design of the agents' internal processes may also require further analysis of the qualitative data through the lens of a framework capturing the agents' internal processes.

Agent architectures such as BDI [23] provide frameworks focused on capturing the agents' internal processes. However, agent architectures are often described in a qualitative manner, making their implementation in the model formalization open to different interpretations and, hence, difficult to reproduce. Generic models such as the Generic Agent Model (GAM) can provide a formalized understanding the internal processes occurring within the agents e.g. according to a particular agent architecture. *The advantage of using generic models is that different agent architectures can be captured and compared through the same formal language*[6]. For instance, several applications of GAM have been proposed that capture different agent architectures (e.g. normative, cooperative, or BDI) in a formalized and non-ambiguous way [24] (cf. Section 3.2). These applications of GAM provide the model designer with a series of options in the way the agents' internal processes are designed and formalized through the selected generic model, given the key agents and their interactions captured by a particular system composition.

Developing a model concept formalization entails the following steps. First, a generic model is selected. GAM only assumes some of the general characteristics

[6] Ontologies can also be used to formalize an agent architecture in a rigorous way. However, ontologies can capture solely the declarative knowledge of an agent architecture, while overlooking the procedural knowledge (i.e. the rules followed by the agents when carrying put particular tasks)) [46]. Conversely, generic models can capture both the declarative and procedural knowledge of an agent architecture [24].

of an agent [15, 28] and could be selected in most cases if its general assumptions are shared by the researchers who decide to use it. However, more specific generic models capturing particular agent architectures may also be selected depending on the chosen modelling purpose and the adopted modelling strategy as discussed by [17]. Second, the selected generic model is used to interpret and structure a) the system composition from the previous step, (b) the results of the framework application (analysis of system's configuration, change, and performance), (c) previously or newly collected qualitative data[7] to develop a model's concept formalization. This process occurs in two iterative steps: (a) specialization of the generic model's process composition and (b) instantiation of the information types included in the generic model's knowledge composition (cf. P. 2.5).

The *specialization* of a generic model's process composition based on the system composition is carried out by individuating a task hierarchy, task inputs and outputs, information exchange among tasks, and the delegation of the tasks[8]. First, the task hierarchy is refined based on the system composition. The activities and interactions of the entities found in the system's composition are assigned as sub-tasks to the matching categories of tasks included in the selected generic model. For instance, tasks that set the goals of an agent (e.g. by assuming or changing roles) or carry out decision making activities, are assigned to the agent's Own Process Control (OPC), whereas tasks that involve interaction with the world or environment such as moving or collecting information from the surroundings are assigned to the Management of World Interaction (MWI) task (cf. Appendix A).

Second, *additional sub-tasks are added to the task hierarchy which provide the internal processes required to enable an agent's activities and interactions*. These sub-tasks are designed considering the sub-processes that are required for the agent to make choices with respect to some of the activities found in the system composition e.g. selection of information exchange partners. In the case of empirical models, the chosen generic model can also be used to further structure and interpret the previously collected data to guide the design of the agent's internal processes. The researchers can also collect further data specifically meant to guide the design of the agent's internal processes on the basis of the generic model. Such data can then be structured and interpreted through the lens of the generic model to confirm sub-tasks designed based on the system composition, find additional sub-tasks, or verify if any of the task included in the generic model are actually (not) required. In the case of theoretical models, such sub-tasks are designed purely based on the previously obtained system composition, literature, and the tasks included in the chosen generic model.

Third, the *input and output* information of the sub-tasks is defined respectively

[7] In some cases, the researcher may decide to collect further data that is specifically meant to capture the internal processes occurring within the agents. In such cases, the generic model can provide a framework that informs not only the data analysis, but also the data collection [12].

[8] According to [27], task control knowledge is also obtained via the specialization of a generic model's process composition. However, given that task control knowledge defines procedures related to when and how particular tasks are carried out by an agent, the specification of task control knowledge is placed in the later Model Narrative Development step of this methodology.

by considering the information required by the task and the information that the task can provide to other tasks.

Fourth, the *information exchange* among tasks is defined by adding information links across the tasks based on the input and output information. Some of the links required may already be provided by the generic model among the tasks included in such model (e.g. OPC and MWI). In other cases, some of the links included in GAM may not be necessary for the considered application and are excluded from the concept formalization.

Fifth, the tasks are *delegated* (assigned) to the entities (agents and the environment) as found in the system composition phase (e.g. the environment and different agent types).

The *instantiation* of the abstracted information types entails finding new refined information types that are instances of the abstract categories included in the generic model. In the case of GAM, the generic categories of information types are world information, agent information, agent identification, domain actions, and domain agent characteristics. Instances of the information types can be introduced based on the internal processes designed in the specialization of the process composition, e.g. when the sub-tasks found require more refined instances of the information types.For empirical models, the researcher could analyse the results of the framework application (analysis of systems configuration, change and behaviour) through the lens of such generic information types to find the different sub-types of "world information" that the agent perceives from the environment, and thus identify instances of the generic information type "world information". Further, additional instances of the information types may be found by re-analysing the previously or newly collected qualitative data through the lens of the generic information types. If the collected data does not provide sufficient evidence (i.e. theoretical saturation has not been reached [47]) with respect to the considered information types, the researcher may decide to collect further data aimed at verifying, refining and expanding upon the information types found. In the case of theoretical models the information types are instantiated based on the generic model, the result of the specialization and possibly literature.

Given the specialization of the process composition and instantiation of the knowledge composition obtained above the agents, their tasks, and information types can be defined in a software implementable way (e.g. via UML diagrams).

3.5.6. Model Narrative Development:

At this stage, all tasks the agents carry out including their interactions with other agents and with the environment are organized into a narrative. First, the specialization of the task control knowledge is carried out. Task control knowledge dictates when particular tasks are to be executed by the agent and by tasks that have sub-tasks (cf. Appendix A). Secondly, the instantiation of the knowledge bases is carried out in order to define the rules followed by the agents when particular tasks are executed. Specifically, knowledge bases are specified for the tasks that are primitive (i.e. that do not have sub-tasks).

In the case of empirical models, the selected generic model provides a framework to further structure and interpret the collected data, the results of the framework application, system composition, and concept formalization to specialize task control knowledge and instantiate knowledge bases. At this stage, further data may be collected to specifically inform the design of task sequencing (task control knowledge) and agent rules (knowledge bases). In the case of theoretical models, the specialization of task control knowledge and instantiation of knowledge bases is based on the system composition and the chosen generic model.

Given the specialized task control knowledge and instantiated knowledge bases it is possible to *assemble a narrative* to be captured in the model e.g. via pseudocode or through a flow chart. The task control knowledge determines the order of execution of the tasks and their sub-tasks given particular triggering "events" or knowledge states (e.g. incoming information to the task or the successful completion of another task, cf. Appendix A). However, the order of occurrence of the events that trigger the tasks is a deliberate choice of the modeller. As such, a number of narratives can be assembled given the same task control knowledge depending on the considered order of triggering events. The knowledge bases determine the rules followed by the agents within the most elementary tasks (i.e. those which do not have sub-tasks).

3.5.7. Software Implementation:

In this step, the model conceptualization and narrative are implemented in a modelling environment such as NetLogo, Repast Symphony or GAMA. A detailed review to guide the choice of a modelling environment is provided by [48].

3.5.8. Model Evaluation:

Model evaluation is an activity that occurs throughout the development of a model. Evaluation can take different forms including verification and validation. Verification focuses on assessing whether the model corresponds to the intentions of the modeller. Validation is concerned with evaluating if the model corresponds to the reality it aims to capture [41, 49]. Depending on the modelling purpose, validation and verification assume different relative importance [17]. Theoretical models are not directly connected to a particular case study. As such, there is a stronger focus on verification rather than validation. Conversely, empirical models aim to capture a given case study, and therefore typically require a stronger emphasis on validation. Descriptive empirical models do not aim to reproduce a system's performance or change but only to combine knowledge gathered through the case study with previously available knowledge and models. Therefore, such models require solely a validation in terms of their model conceptualization and narrative (structural validation). Other empirical models that aim at reproducing the system performance need to be validated not only in terms of their structure, but also with regards to their ability to reproduce the system's performance or change. In such cases, the results of the analysis of system performance and/or change from the framework application (see Section 3.4) can be used here as the output to be matched by the model.

3.5.9. Abstraction of a new Generic Model

When a generic model is used in the concept formalization and for the development of a model narrative, new tasks and knowledge structures may be introduced which can be abstracted and constitute a new generic model. The resulting generic model can then be re-used in similar situations. For instance, the application of GAM to develop a model for distributed project coordination in engineering consultancies resulted in the definition of a new generic model, namely the Generic Cooperative Agent Model or GCAM [26]. GCAM may be re-used for any situation in which distributed and cooperative project management is of interest, assuming joint intentions, limited time resources, and non-urgent problems. In the case of ABMs designed to target a particular phenomenon of interest in a given system, abstraction entails the design of a new generic model that applies to the considered class of phenomenon of interests. As such, this model can then be re-used to develop models that aim at addressing the same phenomenon of interest in different systems.

3.5.10. Iterative Model and Conceptual Framework Development

The model development phase is likely to produce new knowledge regarding relevant systems characteristics, attributes, relationships or system's performance that are not included in the conceptual framework designed in phase one. As such, this knowledge can be incorporated back in the conceptual framework for future use.

3.6. Conclusion

In this chapter, a methodology was designed to develop conceptual frameworks and agent-based models (ABMs) to study phenomena of interest, including ACDIS. The methodology fills a gap in the literature by providing the means to (a) strike a balance between the comparability of framework-based methodologies and the flexibility of case-based methodologies and (b) to provide versatility by enabling to develop ABMs with both theoretical and empirical purposes while maintaining rigour. The methodology is divided into two steps. First, a conceptual framework tailored to a phenomenon of interest is developed. Second, the conceptual framework, together with generic models, is used to develop an ABM.

The way the conceptual framework and generic models support model design depends on whether the model is directly related to a case study (empirical) or not (theoretical) [17]. In the case of *empirical models* the conceptual framework is applied to a case study to analyse the system's configuration, change, and performance. Based on these analyses, a context-specific conceptual model (a system composition) is developed which captures the agents, their interactions with other agents, and the indicators of system's performance and change that are key for the considered phenomenon of interest. Next, a generic model [24] capturing a particular agent architecture is selected depending on the modelling purpose and strategy [17]. Such a generic model is then used to analyse the results of the conceptual framework application, system composition, and possibly additional qualitative data from the case study to inform the design of the internal processes that drive the agents' interactions. The result is an empirical ABM.

In the case of *theoretical models*, the conceptual framework provides an inventory of (a) systems characteristics, attributes and relationships of which the researchers may decide to introduce instances in the considered abstract system and (b) a list of criteria for assessment as indicators of the system's performance that the researchers may wish to study.

This methodology ensures rigour by providing clear steps for translating qualitative data into quantitative ABMs through two frameworks: the conceptual framework developed in the first phase of the methodology and a generic model capturing a specific agent architecture. The methodology balances cross-case comparability and flexibility by using a conceptual framework that is fixed across case studies of the same phenomenon of interest, while allowing for the selection of different generic models and associated agent architectures based on the needs of each specific case. Finally, the methodology provides versatility concerning the modelling purpose by outlining steps to develop both theoretical and empirical ABMs through the lenses of the conceptual framework and generic models.

As shown in Table 1.1, this chapter provides a foundation for answering RQs 1, 2, and 3. It contributes to answering RQ1 by outlining the methodological steps for developing a conceptual framework for ACDIS. Additionally, it contributes to addressing RQ2 and RQ3 by designing a methodology for ABM development.

This methodology is illustrated with the case study of ACDIS in Jakarta in the next two chapters. These chapters also enable the assessment of the methodology's rigour, balance of comparability and flexibility, and versatility.

REFERENCES

[1] V. Nespeca, T. Comes, and F. Brazier. “A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry”. In: *JASSS* 26.1 (2023), p. 10. issn: 1460-7425. doi: 10.18564/jasss.5014.

[2] N. Black. “Why we need qualitative research.” In: *Journal of epidemiology and community health* 48.5 (1994), p. 425.

[3] N. Levina and E. Vaast. “The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems”. In: *MIS quarterly* (2005), pp. 335–363.

[4] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. In: *Disasters* 38.s1 (2014), S50–S72.

[5] L. Yang and N. Gilbert. “Getting away from numbers: Using qualitative observation for agent-based modeling”. In: *Advances in complex systems* 11.02 (2008), pp. 175–185.

[6] C. Adam and B. Gaudou. “Modelling Human Behaviours in Disasters from Interviews: Application to Melbourne Bushfires”. In: *JASSS* 20.3 (2017), p. 12. issn: 1460-7425.

[7] J. A. Maxwell. “The value of qualitative inquiry for public policy”. In: *Qualitative Inquiry* 26.2 (2020), pp. 177–186.

[8] M. A. Janssen and E. Ostrom. “Empirically based, agent-based models”. In: *Ecology and society* 11.2 (2006).

[9] B. Edmonds. “Using qualitative evidence to inform the specification of agent-based models”. In: *JASSS* 18.1 (2015), p. 18.

[10] S. Bharwani, M`. Coll Besa, R. Taylor, M. Fischer, T. Devisscher, and C. Kenfack. “Identifying Salient Drivers of Livelihood Decision-Making in the Forest Communities of Cameroon: Adding Value to Social Simulation Models”. In: *JASSS* 18.1 (2015), p. 3. issn: 1460-7425.

[11] A. Ghorbani, A. Ligtvoet, I. Nikolic, and G. Dijkema. “Using institutional frameworks to conceptualize agent-based models of socio-technical systems”. In: *Proceeding of the 2010 workshop on complex system modeling and simulation*. Vol. 3. 2010, pp. 33–41.

[12] A. Ghorbani, G. Dijkema, and N. Schrauwen. “Structuring Qualitative Data for Agent-Based Modelling”. In: *JASSS* 18.1 (2015), p. 2. issn: 1460-7425.

3

[13] S. Bharwani. “Adaptive knowledge dynamics and emergent artificial societies: ethnographically based multi-agent simulations of behavioural adaptation in agro-climatic systems”. In: *University of Kent, UK* (2004).

[14] A. Ghorbani, P. Bots, V. Dignum, and G. Dijkema. “MAIA: a Framework for Developing Agent-Based Social Simulations”. In: *JASSS* 16.2 (2013), p. 9. issn: 1460-7425. doi: 10.18564/jasss.2166.

[15] M. Wooldridge and N. R. Jennings. “Agent theories, architectures, and languages: a survey”. In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1994, pp. 1–39.

[16] N. Gilbert, P. Ahrweiler, P. Barbrook-Johnson, K. P. Narasimhan, and H. Wilkinson. “Computational modelling of public policy: Reflections on practice”. In: *JASSS* 21.1 (2018).

[17] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. “Different Modelling Purposes”. In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[18] J. K. Hazy and B. F. Tivnan. “The impact of boundary spanning on organizational learning: Computational explorations”. In: *Emergence* 5.4 (2003), pp. 86–123.

[19] N. Altay and R. Pal. “Information Diffusion among Agents: Implications for Humanitarian Operations”. In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[20] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. “Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats”. In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

[21] B. Edmonds and L. ní Aodha. “Using Agent-Based Modelling to Inform Policy – What Could Possibly Go Wrong?” en. In: *Multi-Agent-Based Simulation XIX*. Ed. by P. Davidsson and H. Verhagen. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2019, pp. 1–16. isbn: 978-3-030-22270-3. doi: 10.1007/978-3-030-22270-3_1.

[22] J. Badham, P. Barbrook-Johnson, C. Caiado, and B. Castellani. “Justified stories with agent-based modelling for local COVID-19 planning”. In: *JASSS* 24.1 (2021), p. 8.

[23] A. S. Rao and M. P. Georgeff. “Modeling rational agents within a BDI-architecture”. In: *Proceedings of the Second International Conference on Principles of Knowledge Representation and Reasoning*. 1991, pp. 473–484.

[24] F. M. Brazier, C. M. Jonker, and J. Treur. “Principles of component-based design of intelligent agents”. In: *Data & Knowledge Engineering* 41.1 (2002), pp. 1–27.

[25] F. M. Brazier, B. M. Dunin-Keplicz, N. R. Jennings, and J. Treur. “DESIRE: Modelling multi-agent systems in a compositional formal framework”. In: *IJCIS* 6.01 (1997), pp. 67–94.

[26] F. M. Brazier, C. M. Jonker, and J. Treur. “Formalisation of a cooperation model based on joint intentions”. In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1996, pp. 141–155.

[27] F. M. Brazier, C. M. Jonker, and J. Treur. “Compositional design and reuse of a generic agent model”. In: *Applied Artificial Intelligence* 14.5 (2000), pp. 491–538.

[28] M. Wooldridge and N. R. Jennings. “Intelligent agents: Theory and practice”. In: *The knowledge engineering review* 10.2 (1995), pp. 115–152.

[29] S. A. Kauffman. *The Origins of Order: Self-organization and Selection in Evolution*. en. Oxford University Press, 1993. isbn: 978-0-19-507951-7.

[30] L. K. Comfort, K. Ko, and A. Zagorecki. “Coordination in Rapidly Evolving Disaster Response Systems: The Role of Information”. en. In: *American Behavioral Scientist* 48.3 (Nov. 2004), pp. 295–313. issn: 0002-7642. doi: 10.1177/0002764204268987.

[31] D. Anzola, P. Barbrook-Johnson, and J. I. Cano. “Self-organization and social science”. In: *Computational and Mathematical Organization Theory* 23.2 (2017), pp. 221–257.

[32] F. Brazier, P. v. Langen, S. Lukosch, and R. Vingerhoeds. “Complex systems: design, engineering, governance.” In: *Projects and People: Mastering Success*. NAP - Process Industry Network, 2018, pp. 35–60.

[33] R. K. Yin. *Case Study Research: Design and Methods*. en. Google-Books-ID: FzawIAdilHkC. SAGE, 2014. isbn: 978-1-4129-6099-1.

[34] J. M. Epstein. “Agent-based computational models and generative social science”. In: *Complexity* 4.5 (1999), pp. 41–60.

[35] B. Flyvbjerg. “Five misunderstandings about case-study research”. In: *Qualitative inquiry* 12.2 (2006), pp. 219–245.

[36] M. B. Miles and A. M. Huberman. *Qualitative Data Analysis: An Expanded Sourcebook*. en. SAGE, Jan. 1994. isbn: 978-0-8039-5540-0.

[37] J. Fereday and E. Muir-Cochrane. “Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development”. In: *IJQM* 5.1 (2006), pp. 80–92.

[38] H.-F. Hsieh and S. E. Shannon. “Three approaches to qualitative content analysis”. In: *Qualitative health research* 15.9 (2005), pp. 1277–1288.

[39] R. Boero and F. Squazzoni. “Does empirical embeddedness matter? Methodological issues on agent-based models for analytical social science”. In: *JASSS* 8.4 (2005).

3

3

[40] A. Flache, M. Mäs, T. Feliciani, E. Chattoe-Brown, G. Deffuant, S. Huet, and J. Lorenz. “Models of social influence: Towards the next frontiers”. In: *JASSS* 20.4 (2017).

[41] I. Nikolic and A. Ghorbani. “A method for developing agent-based models of socio-technical systems”. In: *2011 International Conference on Networking, Sensing and Control*. Apr. 2011, pp. 44–49. doi: 10.1109/ICNSC.2011.5874914.

[42] K. H. Dam, I. Nikolic, and Z. Lukszo. *Agent-based modelling of socio-technical systems*. Vol. 9. Springer Science & Business Media, 2013.

[43] V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe’er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, and D. L. DeAngelis. “A standard protocol for describing individual-based and agent-based models”. en. In: *Ecological Modelling* 198.1 (Sept. 2006), pp. 115–126. issn: 0304-3800. doi: 10.1016/j.ecolmodel.2006.04.023.

[44] A. Zagorecki, K. Ko, and L. K. Comfort. “Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments”. In: *JASSS* 13.3 (2009), p. 3. issn: 1460-7425.

[45] L. Bateman and E. Gralla. “Evaluating Strategies for Intra-Organizational Information Management in Humanitarian Response”. en. In: *Proceedings of the 15th ISCRAM Conference*. Rochester, NY, 2018, p. 13.

[46] M. H. Zack. “Managing Codified Knowledge”. English. In: *Sloan Management Review* 40.4 (1999). Num Pages: 14 Place: Cambridge, United States Publisher: Massachusetts Institute of Technology, Cambridge, MA, pp. 45–58. issn: 0019848X.

[47] K. M. Eisenhardt. “Building theories from case study research”. In: *Academy of management review* 14.4 (1989), pp. 532–550.

[48] S. Abar, G. K. Theodoropoulos, P. Lemarinier, and G. M. P. O’Hare. “Agent Based Modelling and Simulation tools: A review of the state-of-art software”. en. In: *Computer Science Review* 24 (May 2017), pp. 13–33. issn: 1574-0137. doi: 10.1016/j.cosrev.2017.03.001.

[49] M. Calder, C. Craig, D. Culley, R. De Cani, C. A. Donnelly, R. Douglas, B. Edmonds, J. Gascoigne, N. Gilbert, C. Hargrove, *et al.* “Computational modelling for decision-making: where, why, what, who and how”. In: *Royal Society open science* 5.6 (2018), p. 172096.

4 Conceptual framework for actor-centred disaster information sharing

To support coordinated self-organisation and resilience in disaster response, information sharing must adapt to the emerging roles, responsibilities, and information needs of actors resulting from self-organisation. To address this challenge, this chapter proposes an actor-centred framework for disaster information sharing enabling to analyse the current practice in disaster information sharing, the way it evolves through self-organisation, and the extent to which it supports coordinated self-organisation in a given system. The framework is developed following the steps outlined in Chapter 3 (Section 3.4). A literature review identifies the characteristics of ACDIS, which guide the design of a preliminary list of requirements. These requirements are refined and validated through a case study in Jakarta. The validated requirements are then used to develop a conceptual framework capturing the key characteristics of and requirements for ACDIS from the previous steps. This chapter answers RQ1. Additionally, this chapter validates the first part of the methodology introduced in chapter 3, thereby contributing to answering RQ3.

4.1. 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-organisation process has also introduced new challenges related to coordinating and orchestrating information flows [3–5]. 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

Parts of this chapter are based on: [1, 2].

and responders are locally trying to fill an organisational 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 [6].

Disaster information sharing that facilitates coordinated self-organisation is essential for promoting both coordinated efforts (rather than creating isolated 'bubbles' of action) and self-organisation. The primary challenge in this context lies in the unpredictable nature of actors' roles, responsibilities, and corresponding information needs resulting from self-organisation. in these conditions, information flows must continuously adjust to deliver the necessary information to the actors that need it. Recent disaster case studies show the ongoing difficulty of supporting coordinated self-organisation through information sharing [7, 8]. Consequently, crucial information is often lacking, inaccessible, or uncertain [9, 10]. Additionally, the urgency and constant influx of information typical in disaster scenarios can lead to information overload, making it challenging for actors to search for or process the information effectively [11, 12].

As mentioned in Chapters 1 and 2, studying disaster information sharing that can support coordinated self-organisation calls for an *actor-centred perspective* due to the decentralized nature of self-organisation. In the field of disaster information sharing, there are several studies that model information diffusion [13, 14], provide experimental insights on orchestrating information flows [12] or present case studies [9, 10]. However, a conceptual framework is missing that embraces an actor-centred perspective and allows to systematically analyse disaster information sharing and it ability to support coordinated self-organisation. In this chapter, an actor-centred framework is designed and validated that enables the analysis the current practice of disaster information sharing, including the way changes occur via self-organisation and the extent to which coordinated self-organisation is supported.

The conceptual framework is designed according to the steps outlined in the previous chapter, Section 3.4: Literature review, Requirements Design, Case Study, Framework design. The following sections illustrate these steps.

4.2. Literature review

The review of relevant literature and existing ABMs was narrative. Specifically, literature from the field of multi-actor systems, self-organisation and information sharing in crisis response was considered given these fields are key to study disaster information sharing. Additionally, a review of the existing ABMs on disaster information sharing was carried out. This review led to the identification of the *phenomenon of interest* as disaster information sharing that can support both coordination and self-organisation in disaster response by satisfying the continually shifting information needs of individual actors. This calls for an actor-centred perspective. As such, the *unit of analysis* chosen for the conceptual framework is that of an individual person (or actor). A list of relevant *system's characteristics and attributes* was derived from the current literature and existing

ABMs[1] for the fields of Multi-Actor Systems, Self-Organisation, and Information Management as shown in the following sections.

4.2.1. 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 [16]. 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 [10, 17].

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 [18]. 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 [19]. 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 [19]. 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 [20]. 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 sharing 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 [4, 20].

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 [21]. Examples of groups are families, communities, and organisations [22]. 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 organisations and groups. Within groups the actors have weak or strong (social) ties constituting *networks* that enable them to exchange information and mobilize resources [23, 24], possibly facilitated by information technology [25]. Groups *can* have *coordination structures*[2], that are based on established hierarchical and functional divisions of roles, with clear

[1] For instance, the conceptualization of the environment in a crisis as a series of cascading shocks producing information needs was introduced as in [15].

[2] Called structures from this point on.

responsibilities and mandates following standardized operating procedures [26, 27]. Structures can be within a group or across different groups. Additionally, the actors operate in an *environment* that can influence their activities [28].

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 [22]. 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.

4.2.2. Self-Organisation

Self-organisation is the spontaneous emergence of order [29] or recognizable patterns in a system, in which multiple entities operate autonomously. In multi-actors systems, these entities are actors and self-organisation takes place as a consequence of their decisions [30].

Self-organisation is typical for disaster response [30]. 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 [20, 31]. The groups and their structures and networks change as actors create new connections [25], form and join groups, and establish or modify structures within and across groups [32, 33]. While self-organisation 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 [3, 4]. Although self-organisation provides an opportunity for faster and better tailored response, it can also create fragmentation and inefficiencies [4, 6, 22]. Coordinating the emergent activities of the actors and groups is hence essential for efficient disaster response and resilience [34]. Information is crucial for supporting coordination [10, 28]. Whether actors obtain the information they need depends on the way information flows are collectively managed in the system [10, 35]. Such information flows change through self-organisation, e.g. when the actors adjust the way they share information [5, 36]. In sum, role & structural change and networking (building new connections, and establishing or joining groups) are identified as self-organisation and coordination activities, considered as a key characteristic of disaster information sharing.

4.2.3. 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 [20, 35]. Much research has been carried out in the field of *information quality* to define what characterizes information needs [9, 37]. Some of these characteristics have been included in the humanitarian information management principles adopted by the United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA) [38]: Relevance, Timeliness, Accessibility, Interoperability, Sustainability, Reliability, and Verifiability. Information is reliable if it is justified in terms of its content or source [39]. The volume and velocity of information can cause information overload, which makes it difficult for the actors to find the information they need [11, 12], or even contributes to discarding or neglecting relevant information [6].

Information management activities are all those tasks carried out to collect, evaluate, process and share information [35]. *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 fulfil 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 characteristics and their attributes are identified:

- Information Management Activities: collecting, evaluating, processing, sharing & storing;
- Information Characteristics: Information quality (Relevance, Timeliness, Accessibility, Interoperability, Reliability, and Verifiability)[3], and Load;

4.3. Requirements design

The requirements design entails the formulation of the system mission and the related functional, behavioural and structural requirements (Cf. Section 3.4.4). The design process took place considering and building on the characteristics and attributes identified in Section 4.2.

4.3.1. Mission

The mission is the purpose of the system. For ACDIS that aims at supporting coordinated self-organisation, the goal is to facilitate both coordination and self-organisation via information. As information is key for coordination (Section 4.2.2), the mission of ACDIS was derived from (i) the general goal of information management to provide the information required to the actors who need it, when

[3] Compared to the information quality characteristics as in [38], Sustainability is not considered as it is most relevant for longer term crises, which are out of scope for this study.

they need it, and (ii) considering the characteristics of such information needs resulting from Section 4.2.3, leading to the following definition:

Mission of ACDIS: to provide relevant, reliable and verifiable information to the actors who need it, when they need it in an accessible manner.

4.3.2. Functional Requirements

Functional requirements describe the functions that a system has to perform to fulfil its mission, taking into account the relevant system's characteristics and their attributes. To this end, the following requirements were designed by deriving the functions needed to achieve the desired 'information characteristics' as in Section 4.2.3.

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)[4]: 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 a disaster (Cf. Section 4.2.1). ACDIS that supports coordinated self-organisation is 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 studying disaster information sharing 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.

[4] Called accessibility from this point on.

4.3.3. Behavioural requirements

Behavioural requirements define (i) the desired system behaviour associated with the fulfilment of the functional requirements 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. The behavioural requirements are shown in the following.

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.

4.3.4. Structural requirements

Structural requirements are the components of the system and their relationships put in place in order to fulfil the behavioural requirements. Structural requirements were derived by considering the characteristics and attributes of ACDIS found in literature (Cf. Section 4.2) 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 4.2.2). Moreover, the characteristics of the actors also influence how particular roles are carried out (Section 4.2.1). Therefore, a framework for the study ACDIS that support coordinated self-organisation 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 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 present informal networks. Structures can be of different types based on the presence of authority and on whether they cross the boundaries of groups (Section 4.2.1). 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, and norms and rules 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 4.2.2). Additionally, actors manage information with the goal of fulfilling information needs (Section 4.2.3), but also operate physically in the environment. The environment can on turn influence the activities actors carry out (Section 4.2.1). 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.

4.4. Case study

This section validates and refines the requirements obtained from theory based on the case study of Jakarta. The following sections introduce the case study, illustrate the data collection and analysis procedures, and outline the findings in the form of a list of validated and refined requirements.

4.4.1. The case of Jakarta

Jakarta is a typical case for studying the phenomenon of ACDIS as (a) the city is affected by frequent flooding due to its rapid subsidence and urbanization processes [40], (b) because of such frequent floods, many self-organized initiatives have been initiated, often aided by social media and messaging apps [41], and (c) the city presents a great diversity of actors, groups, roles and activities relevant for the development of a conceptual framework than can capture such diversity.

Another reason for choosing Jakarta was that at the time of data collection (in 2018) many international organisations were in the city due to the humanitarian response to the Sulawesi Earthquake. This provided the opportunity to interview their representatives in person[5].

Finally, Jakarta was selected as it has been extensively studied by many scholars, increasing the likelihood of accessing additional findings and relevant data if needed (see e.g., [41–45]).

4.4.2. 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 interviews and focus groups, but also documented sources of information. Retrospective

[5] Case-study research in the field of disaster management has to often take advantage of the opportunities that arise when new cases occur (see for instance [7, 8]).

interviews and focus groups allow participants to answer questions from their own experience[6].

Given that the Jakarta case study is intended to validate and refine the requirements for designing the conceptual framework, event and participant selection was guided by the previously identified requirements to ensure that the data collected would effectively serve this purpose (Cf. Section 4.3).

First, to ensure 'Diversity' (Cf. Section 4.3.2), events of different magnitude were covered, involving in some cases only local communities, and in others also national and international actors and groups[7]. Participants were selected among those who responded to or were affected by the considered events. These participants included actors assuming different roles and representing various groups, including both community members and formal organisations involved in disaster response. These choices were made to validate if the framework was able to cover the broad diversity presented by the case study[8], or judge if further adjustments were required. Second, the 'Distinction between Actors and Roles' requirement (Cf. 4.3.4) was addressed by selecting participants likely to shift roles over time, with particular attention to communities where such transitions are common (e.g., individuals becoming community responders)—a dynamic also observed, though less frequently, among professionals [22, 31]. Third, the participant selection reflected the 'Distinction between Structures and Networks' requirement (Cf. 4.3.4), ensuring the inclusion of participants operating within formal structures, informal networks, or across both. Finally, additional participants were found during 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[9]) took place in the neighbourhoods and involved various members of the community including leaders, teachers, factory workers, and representatives of

[6]These data collection procedures were approved by the Ethical review board of the Open University, UK and by TU Delft, The Netherlands.

[7]While many interviewees among the international actors were humanitarian responders working remotely on the Sulawesi earthquake response from Jakarta, the interviews did not focus on this event. Rather, they were focused on past events that occurred in the city of Jakarta. As such, the informants could retrospectively think about these events. The unfolding Sulawesi disaster naturally came up when discussing previous disasters, but this occurred only in a few instances.

[8]This broad inclusion of participants also served as a sampling strategy aimed at limiting biases introduced by retrospection and ensuring the sample was representative of the case study context [46, 47].

[9]Marunda and Kampung Melayu share key characteristics, as both are frequently affected by flooding in Jakarta and rely on effective information exchange—within the community and with external actors such as NGOs and authorities—to support coordination, self-organization, and strengthen their resilience. This is reflected in their comparable community-wide evacuation plans and the development of informal yet effective information-sharing practices. The selection of these communities was initially supported by an exploratory interview and later corroborated through data analysis. Given their similarities, the two communities can be treated as a single case, without the need for an embedded design that separates and subsequently integrates their analysis.

the local response team. The participants covered a broad range of demographics. Table 4.1 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. Given that most local community members did not speak English, translators were hired to interpret in real time the questions posed by the researchers and the responses from the interviewees.

Table 4.1: 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 4.2). 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 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.

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
Stage 3: Information	Information needed to address the situations, as well as the information available that could be shared.	Information Quality (Relevance, Timeliness, and Accessibility) and Load.
Stage 4: Obtaining Information	How was the information obtained? From what sources and which activities, methods, and tools were involved.	Activities, Groups, Roles (formal and informal), Operations, and Environment

Table 4.2: Stages of the interview protocol, their contents, and & DMIS characteristics they target.

4

4.4.3. Data Analysis

The recordings from the interviews and focus groups were then transcribed and analysed using a platform for qualitative data management and analysis[10]. A hybrid deductive and inductive coding approach was adopted. First, an initial coding scheme was designed to capture the requirements designed based on literature (Cf. Section 4.3). This approach was meant to validate the requirements designed via their occurrence in the collected data (deductive approach). Further, while thematically analysing the interviews, also open coding was carried out in parallel to refine the existing requirements and possibly find new ones (inductive approach). Code counting was carried out to have an overview of number of the code instances found. Further, sample quotes were selected from the interviews and focus groups to show supporting evidence for the validated and refined list of requirements and sub-requirements.

The codes were divided into requirements (first order) and their sub-requirements (second order). Requirements were distinguished from sub-requirements by recognizing that sub-requirements offer more detailed guidance on specific aspects within the broader scope of a requirement. For instance, a requirement like 'Actors' presents sub-requirements such as 'Skills, Experience, Knowledge, and Preferences,' which outline the specific attributes of actors that need to be considered.

4.4.4. Findings

Compared to the initial 6 first order codes and 22 second order codes distinguished from the requirements, 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 sub-requirements. In such situations, the definitions associated with these sub-requirements were modified accordingly.

The list of codes obtained in the data analysis, together with their updated definition is provided in Table 4.3. The table also includes the code count, the sample quotes and their IDs.

Table 4.3: Findings from the field: list of requirements, sub-requirements, code count, sample quotes, and quote IDs. The attributes whose definitions were modified via open coding are shown in bold.

Requirem.	Sub-requirements	# Codes	Sample Quotes	Quote ID
Actors (Structural)	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	1
	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	2

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

Requirem.	Sub-requirements	# Codes	Sample Quotes	Quote ID
	Knowledge: non-procedural knowledge from info gathered during disasters or from education.	30	'*if the height in Depok is three meters there will be no flood in here*' Kampung Melayu CL	3
	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	4
Roles (Structural)	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	5
	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	6
	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	7
	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	8
	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	9
Groups (Structural)	Info. Sharing 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	10
	Info. Sharing 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	11
Activities (Structural)	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	12
	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	13
	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	14

Requirem.	Sub-requirements	# Codes	Sample Quotes	Quote ID
	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	15
Information characteristics (behavioural)	**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	16
	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	17
	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	18
	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	19
	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	20
	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 paralyse the ability for residents to make decisions."'*. Petabencana CLN	21
Environm. (Structural)	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	22

Two of the behavioural requirements, namely relevance and timeliness had to be updated as their definitions from literature did not match the views of the case study participants (Cf. Table 4.3). Relevance is the degree to which information by the actors matches their intended use. The case study showed that such a definition is valid. However, two additional factors were found that determine the relevance of information. Such factors are (a) the level of aggregation of information (e.g. summarized for a region or, point by point) and (b) the spatial location to which the information refers. For example, when asked about the way information is displayed in their crowdsourcing platform[11], the Community Liaison

[11]This platform is provided by PetaBencana, an NGO that develops and maintains it as an open-source tool. Information concerning the platform is available at the link https://info.petabencana.id/

officer from the NGO Petabencana mentioned how information is provided as a summary over an area in order to give an overview. The user is also able to zoom to areas of interest in order to get the information required at specific locations (Cf. Quote 16, Table 4.3). As such, the definition of Relevance was extended to include the aggregation and spatial location of information as shown in Table 4.3.

In the case of Timeliness, the definition was completely revisited based on the findings from the case study. The literature points to timeliness as the degree to which information is up to date as designed in Section 4.3 based on e.g. [9, 38]. Such definition is independent from the context in which the receiver is placed and only depends on the currency of information. However, the data analysis revealed how the participants mentioned timeliness as the need to obtain information by the time they require it given the context in which they are placed. For instance, when asked about the way information quality could be improved, one of the community members from Kampung Melayu shared that in some cases a second wave of flooding can occur after they already started their recovery activities (clearing their house from debris) (Cf. Quote 17, Table 4.3). In this context, information concerning a second flood wave would be timely if provided by the time community members start their recovery activities. To match this perspective, the definition of timeliness was updated as shown in Table 4.3.

4.5. Framework Design

As introduced in the Section 3.4.1, a conceptual framework that enables the analysis of an existing system or construct an abstract one to inform the development of ABMs for studying a phenomenon of interest should include the system's characteristics and their attributes, relationships among characteristics, and criteria for assessment (Cf. Figure 3.2). This section shows how a conceptual framework with its system's characteristics, attributes, relationships, and criteria for assessment was designed based on the refined and validated list of structural and behavioural requirements obtained in the previous sections.

Firstly, structural requirements provided the *characteristics* of the system to be captured in the conceptual framework, and the sub-requirements provided the attributes of such characteristics. Each characteristic was included as an independent component of the conceptual framework with the associated attributes. For instance, "actors" and "roles" are characteristics that were included as conceptual framework components. The attributes of the "actors" characteristic include "skills" and "knowledge" given these were found to be sub-requirements of "actors" (Cf. Table 4.3).

Secondly, structural requirements also provided the *relationships* among characteristics. When the relationships were vertical as in the case of "belongs to" or "can have one or more" then the characteristics were organized hierarchically. For instance, actors and roles have a vertical relationship dictated by the "distinction between actors and roles" structural requirement according to which actors "can have one or more" roles (Cf. 4.3). Conversely, when the relationships were horizontal as in "affects" or "performs", then such relationships were linked with an arrow and labelled with the corresponding relationship. For example, the actor's activities may lead to the emergence of new groups, and coordination structures and networks for information sharing[12]. As such, actors' activities "affect" groups.

Thirdly, behavioural requirements provided the *criteria for assessment* necessary to evaluate the extent to which the system performs according to the desired behaviour or performance. Specifically, the criteria for assessment are information relevance, timeliness, accessibility, reliability, verifiability, and load.

The following new definitions were introduced and used in the design process.

- *Information Sharing Structures:* represent the ways roles and their relationships are organized, and the procedures and information sharing channels adopted to perform activities that aim at addressing information needs such as information collection, sharing, storing, and processing.

- *Information Sharing 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 Sharing:* composed of the Information Sharing 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.

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

- *Criteria for the assessment*: criteria used to analyse the extent to which the current practice supports coordinated self-organisation via information. Such criteria are designed based on the behavioural requirements and are: relevance, timeliness, accessibility, reliability, verifiability and load (see Section 4.3.3 for the definitions).

The design process resulted in the framework shown in Figure 4.1. This conceptual framework has the threefold purpose of providing the means to analyse (a) the current practice of disaster information sharing in a case study representing the way information is collectively managed (shared, collected, processed, and stored) in a system (system's configuration), (b) the way such practice changes through self-organized bottom-up processes (system's change), and (c) the extent to which the current practice supports coordinated self-organisation as measured by the criteria for assessment (system's performance).

[12] Here called information sharing structures and networks.

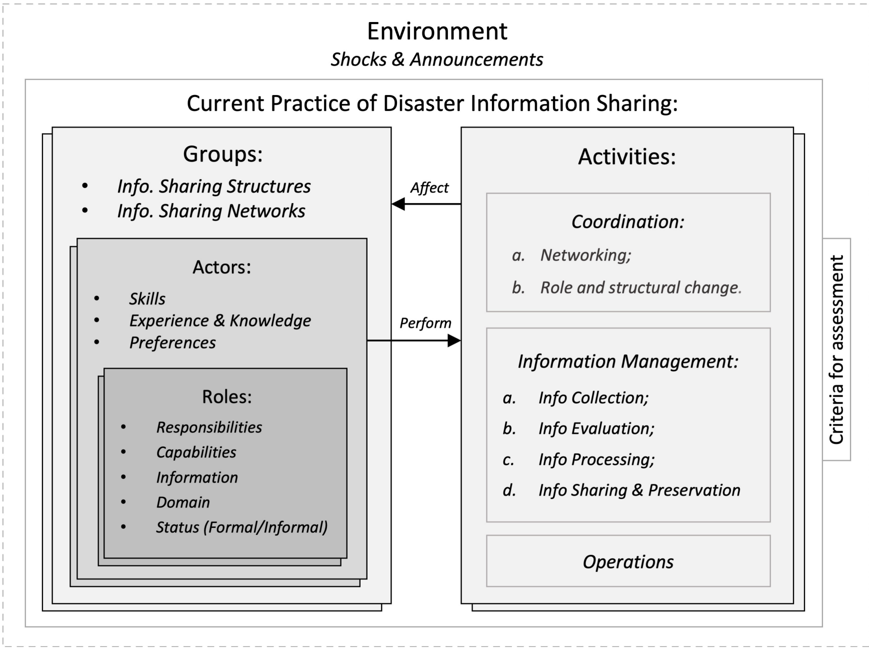

Figure 4.1: Developed Conceptual Framework. The criteria for assessment are information relevance, timeliness, accessibility, reliability, verifiability, and load.

4.6. Discussion and Conclusion

This chapter fills a gap in the literature by proposing a framework for studying ACDIS that supports coordinated self-organisation. The framework is designed to enable the analysis of the current practice of disaster information sharing in terms of its configuration, change through self-organisation, and performance as the ability to support coordinated self-organisation via information.

A literature review enable to define the characteristics of ACDIS. These informed the design of the mission, and the associated functional, behavioural and structural requirements for ACDIS. Such requirements were then validated and refined based on the case study of disaster information sharing in Jakarta. More specifically the behavioural requirements "timeliness" and "relevance" were adapted to the findings from the case study. The result informed to design an actor-centred conceptual framework for disaster information sharing.

As shown in Table 1.1, this chapter addresses RQ1 and contributes to addressing RQ3. It addresses RQ1 by developing an actor-centred conceptual framework for disaster information sharing, capturing its key characteristics and requirements. Additionally, the chapter contributes to answering RQ3 by illustrating how phase one of the methodology developed in Chapter 3 enables the rigorous development of a conceptual framework based on qualitative case study research and existing literature. Furthermore, the chapter demonstrates that the first part of this methodology also provides flexibility to study phenomena lacking an existing conceptual framework by enabling the development of such a framework.

In the next, chapter the conceptual framework is applied to the case of Jakarta to inform the development of an empirical ABM of ACDIS.

REFERENCES

[1] V. Nespeca, T. Comes, K. Meesters, and F. Brazier. "Towards Coordinated Self-organization: An actor-centered framework for the design of Disaster Management Information Systems". In: *IJDRR* 51 (2020), p. 101887. issn: 2212-4209. doi: 10.1016/j.ijdrr.2020.101887.

[2] V. Nespeca, T. Comes, and F. Brazier. "A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry". In: *JASSS* 26.1 (2023), p. 10. issn: 1460-7425. doi: 10.18564/jasss.5014.

[3] L. Palen, K. M. Anderson, G. Mark, J. Martin, D. Sicker, M. Palmer, and D. Grunwald. "A Vision for Technology-mediated Support for Public Participation & Assistance in Mass Emergencies & Disasters". In: *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference*. ACM-BCS '10. Swinton, UK, UK: British Computer Society, 2010, 8:1–8:12. isbn: 978-1-4503-0192-3.

[4] S. Waldman and K. Kaminska. *Connecting emergency management organizations with digitally enabled emergent volunteering Literature review and best practices*. Tech. rep. Defence Research and Development Canada, Dec. 2015.

[5] A. Silver and L. Matthews. "The use of Facebook for information seeking, decision support, and self-organization following a significant disaster". en. In: *Information, Communication & Society* 20.11 (Nov. 2017), pp. 1680–1697. issn: 1369-118X, 1468-4462. doi: 10.1080/1369118X.2016.1253762.

[6] T. Comes, B. V. d. Walle, and L. V. Wassenhove. "The coordination-information bubble in humanitarian response: theoretical foundations and empirical investigations". en. In: *Production and Operations Management* (2020). issn: 1937-5956. doi: 10.1111/poms.13236.

[7] T. Comes, O. Vybornova, and B. Van de Walle. "Bringing structure to the disaster data typhoon: an analysis of decision-makers' information needs in the response to Haiyan". In: *2015 AAAI Spring Symposium Series*. 2015.

[8] H. Baharmand, T. Comes, and M. Lauras. "Supporting group decision makers to locate temporary relief distribution centres after sudden-onset disasters: A case study of the 2015 Nepal earthquake". In: *IJDRR* 45 (2020), p. 101455.

[9] N. Bharosa and M. Janssen. "Principle-Based Design: A Methodology and Principles for Capitalizing Design Experiences for Information Quality Assurance". en. In: *Journal of Homeland Security and Emergency Management* 12.3 (Jan. 2015). issn: 1547-7355, 2194-6361. doi: 10.1515/jhsem-2014-0073.

4

[10] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. en. In: *Disasters* 38.s1 (Apr. 2014), S50–S72. issn: 1467-7717. doi: 10.1111/disa.12052.

[11] T. Comes. “Cognitive biases in humanitarian sensemaking and decision-making lessons from field research”. In: *2016 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*. IEEE. 2016, pp. 56–62.

[12] B. Van de Walle, B. Brugghemans, and T. Comes. “Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination”. In: *IJHCS* 95 (Nov. 2016), pp. 66–79. issn: 1071-5819. doi: 10.1016/j.ijhcs.2016.05.001.

[13] N. Altay and R. Pal. “Information Diffusion among Agents: Implications for Humanitarian Operations”. In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[14] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. “Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats”. In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

[15] J. Meijering. *Information diffusion in complex emergencies: A model-based evaluation of information sharing strategies*. Apr. 2019.

[16] T. W. Malone and K. Crowston. “The Interdisciplinary Study of Coordination”. In: *ACM Comput. Surv.* 26.1 (Mar. 1994), pp. 87–119. issn: 0360-0300. doi: 10.1145/174666.174668.

[17] A. Sebastian, K. Lendering, B. Kothuis, A. Brand, S. Jonkman, P. Gelder, B. Kolen, M. Comes, S. Lhermitte, K. Meesters, B. van de Walle, A. Ebrahimi Fard, S. Cunningham, N. Khakzad, and V. Nespeca. *Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Tech. rep. Delft, South Holland, NL: TU Delft, Oct. 2017.

[18] L. L. Salvadó, M. Lauras, T. Comes, and F. Bénaben. “Structuring Humanitarian Supply Chain Knowledge Through a Meta-Modeling Approach”. en. In: *The Palgrave Handbook of Humanitarian Logistics and Supply Chain Management*. Ed. by G. Kovács, K. Spens, and M. Moshtari. London: Palgrave Macmillan UK, 2018, pp. 491–521. doi: 10.1057/978-1-137-59099-2_16.

[19] CEEP. *Teamwork Exercise: Discussion of Roles and Responsibilities*. 2013.

[20] M. Turoff, M. Chumer, B. V. d. Walle, and X. Yao. “DERMIS: The Design of a Dynamic Emergency Response Management Information System”. English. In: *JITTA : Journal of Information Technology Theory and Application; Hong Kong* 5.4 (2004), pp. 1–35. issn: 15324516.

[21] A. P. Cohen. *Symbolic Construction of Community*. en. Routledge, Mar. 2013. isbn: 978-0-203-13168-8. doi: 10.4324/9780203131688.

[22] J. Whittaker, B. McLennan, and J. Handmer. “A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges”. In: *IJDRR* 13 (Sept. 2015), pp. 358–368. issn: 2212-4209. doi: 10.1016/j.ijdrr.2015.07.010.

[23] F. K. Boersma, J. E. Ferguson, P. Groenewegen, and J. J. Wolbers. “Beyond the myth of control: Toward network switching in disaster management”. English. In: *Proceedings of the 11th International ISCRAM Conference*. 2014, pp. 123–127.

[24] D. P. Aldrich and M. A. Meyer. “Social Capital and Community Resilience”. en. In: *American Behavioral Scientist* 59.2 (Feb. 2015), pp. 254–269. issn: 0002-7642. doi: 10.1177/0002764214550299.

[25] J. Tasic and S. Amir. “Informational capital and disaster resilience: the case of Jalin Merapi”. en. In: *Disaster Prevention and Management: An International Journal* 25.3 (June 2016), pp. 395–411. issn: 0965-3562. doi: 10.1108/DPM-07-2015-0163.

[26] J. R. Galbraith. “Organization Design: An Information Processing View”. en. In: *Interfaces* 4.3 (May 1974), pp. 28–36. issn: 0092-2102, 1526-551X. doi: 10.1287/inte.4.3.28.

[27] R. R. Dynes and B. Aguirre. “Organizational Adaptation To Crises: Mechanisms Of Coordination And Structural Change”. en. In: *Disasters* 3.1 (Mar. 1979), pp. 71–74. issn: 03613666. doi: 10.1111/j.1467-7717.1979.tb00200.x.

[28] L. K. Comfort, K. Ko, and A. Zagorecki. “Coordination in Rapidly Evolving Disaster Response Systems: The Role of Information”. en. In: *American Behavioral Scientist* 48.3 (Nov. 2004), pp. 295–313. issn: 0002-7642. doi: 10.1177/0002764204268987.

[29] S. A. Kauffman. *The Origins of Order: Self-organization and Selection in Evolution*. en. Oxford University Press, 1993. isbn: 978-0-19-507951-7.

[30] L. K. Comfort. “Self-Organization in Complex Systems”. In: *Journal of Public Administration Research and Theory: J-PART* 4.3 (1994), pp. 393–410. issn: 1053-1858.

[31] K. Haynes, D. K. Bird, and J. Whittaker. “Working outside ‘the rules’: Opportunities and challenges of community participation in risk reduction”. en. In: *IJDRR* 44 (Apr. 2020), p. 101396. issn: 2212-4209. doi: 10.1016/j.ijdrr.2019.101396.

[32] K. Starbird and L. Palen. “"Voluntweeters": Self-organizing by Digital Volunteers in Times of Crisis”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. New York, NY, USA: ACM, 2011, pp. 1071–1080. isbn: 978-1-4503-0228-9. doi: 10.1145/1978942.1979102.

4

[33] J. Wolbers, K. Boersma, and P. Groenewegen. “Introducing a fragmentation perspective on coordination in crisis management”. In: *Organization Studies* 39.11 (2018), pp. 1521–1546.

[34] W. N. Adger, T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström. “Social-ecological resilience to coastal disasters”. In: *Science* 309.5737 (2005), pp. 1036–1039.

[35] B. Van de Walle, G. Van Den Eede, and W. Muhren. “Humanitarian Information Management and Systems”. en. In: *Mobile Response*. Ed. by J. Löffler and M. Klann. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2009, pp. 12–21. isbn: 978-3-642-00440-7.

[36] J. Sutton, E. S. Spiro, B. Johnson, S. Fitzhugh, B. Gibson, and C. T. Butts. “Warning tweets: serial transmission of messages during the warning phase of a disaster event”. en. In: *Information, Communication & Society* 17.6 (July 2014), pp. 765–787. issn: 1369-118X, 1468-4462. doi: 10.1080/1369118X.2013.862561.

[37] Y. W. Lee, D. M. Strong, B. K. Kahn, and R. Y. Wang. “AIMQ: a methodology for information quality assessment”. In: *Information & Management* 40.2 (2002), pp. 133–146. issn: 0378-7206. doi: https://doi.org/10.1016/S0378-7206(02)00043-5.

[38] B. Van de Walle and T. Comes. “On the Nature of Information Management in Complex and Natural Disasters”. In: *Procedia Engineering*. Humanitarian Technology: Science, Systems and Global Impact 2015, HumTech2015 107 (Jan. 2015), pp. 403–411. issn: 1877-7058. doi: 10.1016/j.proeng.2015.06.098.

[39] A. Vedder and R. Wachbroit. “Reliability of information on the Internet: Some distinctions”. en. In: *Ethics and Information Technology* 5.4 (2003), pp. 211–215. issn: 1388-1957. doi: 10.1023/B:ETIN.0000017738.60896.77.

[40] H. Z. Abidin, H. Andreas, I. Gumilar, and J. J. Brinkman. “Study on the risk and impacts of land subsidence in Jakarta”. en. In: *Proceedings of the International Association of Hydrological Sciences* 372 (Nov. 2015), pp. 115–120. issn: 2199-899X. doi: 10.5194/piahs-372-115-2015.

[41] R. van Voorst. “Formal and informal flood governance in Jakarta, Indonesia”. en. In: *Habitat International*. Decentralising Disaster Governance in Urbanising Asia 52 (Mar. 2016), pp. 5–10. issn: 0197-3975. doi: 10.1016/j.habitatint.2015.08.023.

[42] M. A. Marfai, A. B. Sekaranom, and P. Ward. “Community responses and adaptation strategies toward flood hazard in Jakarta, Indonesia”. In: *Natural hazards* 75 (2015), pp. 1127–1144.

[43] Y. Budiyono, J. Aerts, J. Brinkman, M. A. Marfai, and P. Ward. “Flood risk assessment for delta mega-cities: a case study of Jakarta”. In: *Natural hazards* 75 (2015), pp. 389–413.

[44] F. P. Flores, Y. T. Prasetyo, B. P. Grahani, R. P. Lukodono, O. P. Benito, A. A. N. P. Redi, M. M. L. Cahigas, R. Nadlifatin, and M. J. J. Gumasing. "Determining factors influencing flood preparedness among citizens in Jakarta: A protection motivation theory approach". In: *Environmental Development* 51 (2024), p. 101042.

[45] T. A. Kurniawan, C. Meidiana, H. H. Goh, D. Zhang, M. Jiang, M. H. D. Othman, A. Anouzla, F. Aziz, M. Mahmoud, M. I. Khan, *et al.* "Social dimensions of climate-induced flooding in Jakarta (Indonesia): The role of non-point source pollution". In: *Water Environment Research* 96.9 (2024), e11129.

[46] K. M. Eisenhardt and M. E. Graebner. "Theory Building From Cases: Opportunities And Challenges". In: *Academy of Management Journal* 50.1 (Feb. 2007), pp. 25–32. issn: 0001-4273. doi: 10.5465/amj.2007.24160888.

[47] M. Q. Patton. *Qualitative research & evaluation methods: Integrating theory and practice*. Sage publications, 2014.

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5
Design of an ABM of actor-centred disaster information sharing

Agent-based modelling and simulation enable the investigation of emergent dynamics arising from complex relationships across multiple levels of analysis, such as micro, meso, and macro. This modelling paradigm is particularly well-suited for studying disaster information sharing that supports coordinated self-organisation from an actor-centred perspective, which considers the interplay between individual behaviour (micro), group characteristics (meso), and the institutional context in which groups operate (macro). Effective information exchange across groups is especially crucial at the boundary between professional responders and communities. However, an ABM that simulates ACDIS among professional response organisations and communities from an actor-centred perspective is currently lacking.

This chapter addresses this gap and answers RQ2 by developing a descriptive, empirical ABM that enables to study inter-group information exchange between professional response organisations and communities during disasters, using Jakarta as a case study. The ABM is developed by applying the second phase of the methodology proposed in Chapter 3, demonstrating how this phase enables the development of empirical ABMs for studying specific phenomena of interest. The chapter concludes by discussing how Chapter 4 and this chapter demonstrate the rigour, ability to balance flexibility and comparability, and versatility of the methodology proposed in Chapter 3, thereby answering RQ3.

5.1. Introduction

Agent-based modelling is a paradigm well-suited for studying dynamics that emerge from interactions across multiple levels (e.g., micro, meso, and macro)

Parts of this chapter are based on: [1, 2].

within a system [3, 4]. For example, [5] uses this approach to examine how micro-level networking behaviours influence the emergence of inter-group information exchange at the macro level among professional responders during disasters. Additionally, [6] develops an ABM to investigate how individual decision-making at the micro level affects disaster evacuation patterns and fatalities at the macro level. Given its ability to capture multi-level interactions, agent-based modelling is well-suited for studying disaster information sharing that supports coordinated self-organisation from an actor-centred perspective. This perspective considers complex interactions across micro-level individual behaviours (e.g., information-sharing preferences and capacity), meso-level group characteristics (e.g., incentives for information sharing [7]), and macro-level institutional arrangements among multiple groups (Cf. Sections 1.3).

This dissertation focuses on fostering inter-group information exchange between communities and professional response organisations, as this boundary is particularly prone to fragmentation and requires effective communication to support coordinated self-organisation between these two macro groups [8–11]. However, an ABM that enables the study of actor-centred information exchange between communities and professional response organisations during disasters, supporting their coordinated self-organisation, is currently lacking (Cf. Section 2.2.1).

To address this gap and answer RQ2, this chapter develops an empirical ABM of actor-centred disaster information exchange between communities and professional response organisations, based on qualitative research conducted for the Jakarta case study (Cf. Section 4.4). The model serves a descriptive purpose [12], providing a non-reductionist formalization of knowledge gathered from case study research and previous literature, with the goal of supporting future research in the field of ACDIS. This ABM is designed following the steps outlined in the second phase of the methodology introduced in Chapter 3. For this purpose, the conceptual framework developed in Chapter 4 is applied to the Jakarta case, revealing the system's configuration, its changes through self-organisation, and its performance in terms of information quality and load. These findings are organized and interpreted using a generic model, specifically the Generic Agent Model, which guides the systematic development of the ABM.

The following sections describe the steps involved in the second phase of the methodology (see Section 3.5), namely Framework Application, Problem Formulation, System Identification and Composition, Concept Formalization, Model Narrative Development, Software Implementation, and Model Evaluation. Finally, the last section discusses the findings of this chapter and presents the conclusions.

5.2. Framework Application

Even though the specific purpose of the model was not clear yet at this stage, the authors already decided to develop an empirical model. As such, the conceptual framework was applied to the case study. The authors relied on the previously collected data that had already been used during the conceptual framework development phase. The data analysis consisted in going back to the codes assigned during the requirements validation to find instances of the characteristics, attributes, relationships, and criteria for assessment found in the conceptual framework. This allowed the authors to identify the system's configuration (current practice of Disaster IM), change (alteration of the practice) and performance (in terms of the criteria for assessment) as briefly shown in the following.

The analysis of **system's configuration** enabled to identify the instances of the characteristics and attributes that represent the current practice of disaster information sharing. The characteristics identified were the key actors and roles they assume, groups they belong to, information sharing structures and networks through which they share information, activities they carry out, and the environmental factors that play a role in disaster information sharing (shocks and announcements) (Cf. Fig. 4.1). For instance, the data showed how the community members in Marunda rely on their informal connections (IM networks) to exchange information e.g. aided by a WhatsApp group (Cf. quote 3 in Table 4.3).

During the analysis of system's configuration, one system characteristic was found that had not been included in the conceptual framework, namely that of objects. Objects are any non-human entities that can support information sharing and coordination activities of the actors both within and across groups. Examples of objects found in the considered case study are social media (Cf. Quotes 8, Table 4.3) and a WhatsApp group used to share and receive flood warnings in the Marunda community (Cf. Quote 3, Table 4.3).

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The analysis of **system's change** was carried out by analysing the way the activities of the actors affect the configuration of the groups and the actors' roles (Cf. relationship "affect" in Fig. 4.1). The analysis showed how role change can occur not only because of a deliberate choice of the actors, but also through a self-organized process triggered by interactions among the actors. The Information Management Officer (IMO) from UN-OCHA observed how s/he assumed the role of an Informational Boundary Spanner or IBS (Cf. Section 1.4) that would provide the information requested by other actors (belonging to different organisations or groups). However, this role change did not occur via a direct choice, but because of gradually increasing requests for information made by other actors (Cf. Quote 7 in Table 4.3). When other actors realized that the s/he had access to information (Cf. Quote 5 in Table 4.3) and knowledge on the type of information available, they gradually required more and more of the IMO's "services". In other words, *the actors learned that the IMO could provide high quality information and adapted their information collection activities accordingly*. Through this learning process, the IMO gradually assumed the (informal) role of IBS across different organisations[1].

Concerning the analysis of **system's performance**, the performance of the system related to information reliability, verifiability, accessibility and load were found to be acceptable from the perspective of the case study participants. However, the timeliness and relevance criteria were found to be unsatisfactory. For example,

[1]Individually learning who provides high quality information and adjusting information collection activities accordingly is tested in Chapter 6 as a candidate mechanism potentially leading to the emergence of IBSs.

one of interviewees mentioned how in some cases information concerning flood warnings was not received on time (Cf. quote 10 in Table 4.3). Specifically, the analysis of performance showed that the relevance and timeliness of information were lacking especially for those information needs of which the actors were not aware (e.g. flood warnings). To capture the discrepancy in performance among information needs of which the actor were aware or not aware of, a distinction was drawn between latent and known information needs. Known information needs are those that the actors are aware of (e.g. an update on the current water level in a flooded area). As such, actors can search for the information they need. In the case of latent information needs this is not possible as the actors are not aware that they need information (e.g in the case of a flood early warning).

5.3. Problem Formulation

A model with a descriptive purpose was chosen to capture some of the main characteristics and dynamics of the current practice of disaster information sharing in the considered system through an actor-centred perspective. This is a first step in building a simulation environment that can be used for designing and evaluating actor-centred information sharing strategies aimed at supporting coordinated self-organisation in the considered system.

Given the findings of the analysis of system's performance (Cf. Section 5.2), information relevance and timeliness were chosen as the assessment criteria representing the *relevant system's performance* to be captured in the model output. Further, the analysis of system's performance highlighted the need to distinguish between latent and known information needs. As such, the model output includes indicators of information relevance and timeliness for both latent and known information needs.

5.4. System Identification and Composition:

The purpose of the model is to capture disaster information sharing practices within a community, and its interactions with other relevant actors and groups (the professional responders) through an actor-centred perspective. The Marunda community and specifically its most affected community units RW 07, 10, and 11 were chosen as the conceptual framework application revealed that these units presented a rich array of information sharing practices during disasters. Further, to capture other relevant actors the system boundary was extended to include also the governmental and non-governmental organisations and groups that (may) exchange information with the community.

The system composition was designed based on the results of the analysis of system's configuration and change refined and focused within the chosen system's boundaries (narrower compared to those of the system considered for the initial conceptual framework application). As such, only the system's characteristics, their attributes and relationships found within the system boundaries were accounted for. For instance, only deliberate role change was considered for the

Marunda community, as no evidence was found that emergent role change occurs within the chosen system's boundary (Cf. Section 5.2). Deliberate role change can occur when community members become aware of a given shock and decide to change their to role to that of responder. Through the analysis, information was also found on the number of the actors in the considered community units (RWs) and their administrative subdivisions or neighbourhood units (RTs).

The system composition also included modelling choices informed by literature and previous models e.g. regarding the level of abstraction at which particular system's characteristics needed to be captured in the model. For instance, according to the conceptual framework, the environment generates disruptive events (shocks and announcements). *Shocks* represent the cascading effects that occur in the disaster-affected area where the community members are located [13] (e.g. community members are stuck on their roofs without food or water). *Announcements* represent information produced outside the disaster affected area (e.g. a flood early warning) [14, 15]. Capturing shock and announcements is key as they provide the information that the actors need. However, while shock and announcements could have been captured in a more detailed way e.g. by distinguishing among different types of announcement and shocks found in the data, this was not considered relevant for the model. As such, only the two generic types of information, namely shocks and announcements were included in the ABM. Such a choice was based on previously existing disaster information sharing ABMs that consider only one generic type of information e.g. [5, 13, 16]. Further, the number of events occurring every day of simulation were conceptualized as *environmental turbulence* defined as the "*as the frequency with which new information is introduced into the environment*" [17]. The frequency of shocks and announcements per day represent two parameters in the model capturing environmental turbulence.

Figure 5.1 shows the resulting system composition for the Marunda community [2] with the exception of the activities of actors, objects, and the environment which are shown in Table 5.1.

5.5. Model Concept Formalization:

At this stage, a generic model was used to guide the design of the concept formalization based on the system composition from the previous step. GAM was chosen as the generic model to be specialized an instantiated for this application. This choice was made as the more specialized generic models available in [18] were not found to the be suited for the particular case of disaster information sharing[3]. The concept formalization was obtained by specializing and instantiating GAM

[2] The attributes of these characteristics are not presented at this stage, but directly in the model conceptualization due to limitation in space.

[3] One of GAM's applications, namely the Generic Cooperative Agent Model (or GCAM) presented in [18–20], has similarities with the distributed and (partly) cooperative nature of disaster information sharing. However, while disaster response is intrinsically characterized by urgency, GCAM is meant for non-urgent problems in which the agents have time to make joint plans. As such, GCAM is not a suitable generic model for developing ABMs that focus on capturing disaster response situations.

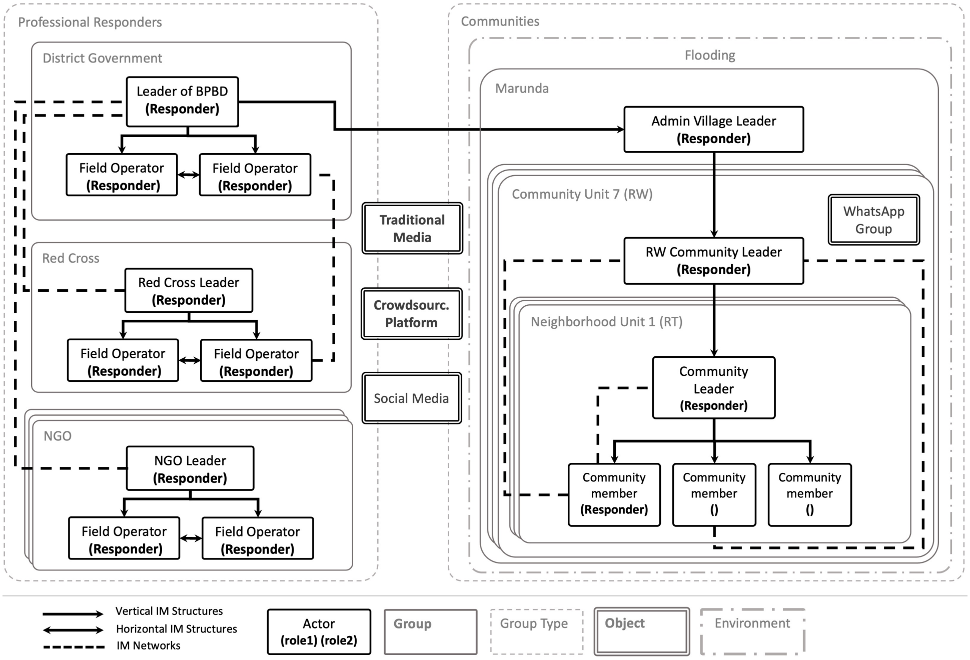

Figure 5.1: System Identification and Composition: configuration of the current practice of Disaster information sharing in Marunda, Jakarta.

through the knowledge captured in the system composition and by analysing the results of the conceptual framework application through the lens of GAM. Specialization and instantiation proceeded in parallel through subsequent refinement and iterations. In the following, an example of specialization and instantiation of GAM based on the system composition is shown with respect to three of the generic model's abstracted tasks, namely "Own Process Control" (OPC), "World Interaction Management" (WIM), and "Maintenance of World Information" (MWI) (Cf. Appendix A).

A *specialization* of GAM was developed to individuate a task hierarchy, tasks input and output, information exchange among tasks, and task delegation to different agent types. First, a task hierarchy was designed by specializing the abstract categories of tasks included in GAM (a) through the activities (i.e. agent's actions and interaction) found in the system composition (Cf. Table 5.1) and (b) by individuating the internal processes required to support such activities. For instance, an activity from the system composition that was chosen to be a specialized task of the OPC was "Manage Responder Role". This task defines whether an actor who was not directly involved in crisis response decides to do so. The choice of specializing the OPC with "Manage Responder Role" was made as this activity can alter an actor's goal, a task that is typically associated with the OPC in GAM (Cf. Appendix A). In other cases, further activities were added

Entity	**Activity Category**	**Activity**	**Sub-activities**
All Actors	Information Management	Collect info	from Environment, Actor or Object
		Receive info	from actor
		Evaluate Info	Check addressed info needs, track shocks found, track info gaps.
		Process Info	Choose from info pile
		Share & Preserve Info	Share to actor, Store in Object, Maintain Info needs
	Coordination	Networking	Manage Collection
	Operations	Move in field	-
		Become Affected	-
Actor: NGO & BNPB Leader	Coordination	Role & Structural Change	Deploy field Operator
			Join Response as group
Actor: Field Operator	Operations	Deploy to field	-
		Leave field	-
Actor: Community Leader	Information Management	Evaluate Info	Assess if required assistance
		Share & Preserve info	Request Assistance to BPBD
Actor: Community Member	Coordination	Role & Structural Change	Manage Responder Role
Object: Traditional Media	Information Management	Process Info	Filter Info
Object: Social Media	Information Management	Share & Preserve Info	Publish Noise (irrelevant info)
Environment	Generate Event	Generate Shocks	Release shocks in affected areas
		Generate Announcements	Release announcements (e.g. info from (flood) monitoring posts)

Table 5.1: System Identification and Composition: activities and sub-activities carried out by the actor and object entities according to the categories of activities introduced in the conceptual framework (Cf. Figure 4.1), and by the environment.

which were not directly found in the system composition, but that *provided the internal processes required to support the activities and interactions found in the system composition*. For instance, a task was missing among those found in the system composition to make decisions with respect to when and how to carry out the Information Management (IM) tasks "Collect info", "Process info", and "Share & preserve info" (Cf. Table 5.1). To this end, a new task was introduced as a sub-task of the OPC called "Determine IM Actions". This task was further specialized with the sub-tasks "Determine IM focus" and "Prepare Information Collection". "Determine IM focus" decides whether the actor agent focuses on processing the received information [4] or on collecting new information. "Prepare

[4]The design choice of having a backlog of information that the actor can access and process at will

Information Collection" assesses whether the actor actually collects information on the basis of the availability of known information needs (Cf. analysis of system's performance in Section 5.2). Further, "collect information", "process information, and "share & preserve information" were added as sub-tasks of the world interaction management component of GAM. The result is shown in figure 5.2.

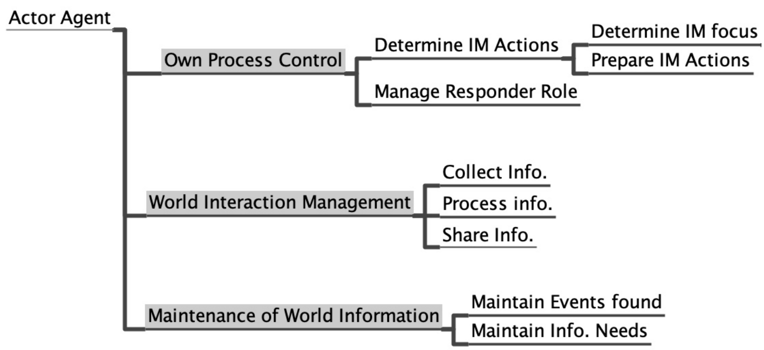

Figure 5.2: Task hierarchy obtained through specialization of the GAM components "Own Process Control", "World Interaction Management", and "Maintenance of World Information" (highlighted in grey in the picture) based on the system composition.

Next, the *tasks input and output* information were designed respectively by considering (a) the information required by each task and (b) the information that the task provides (potentially to other tasks). In the case of "Determine IM actions", the required inputs were the currently known information needs of the actor as actors can only look for information associated with known information needs (Cf. analysis of system's performance in Section 5.2). The output information provided by "Determine IM actions" were the decisions made in terms of information collection, processing, and sharing. Then, to capture the information exchange among tasks, *information links* were designed by connecting the tasks that provide particular outputs with the tasks that require such information as an input. For instance, in the case of "Determine IM Actions", information had to be provided concerning the currently known information needs of the actor. This information is provided by the task MWI and, specifically, by its sub-task "maintain information needs". As such, information links were added to connect "maintain information needs" with "determine IM actions". First, an information link called "known information needs to output" was added between "maintain information needs" and the output of its parent task MWI. Second, the link between MWI and OPC was already included as part of the generic model GAM (Cf. Appendix A). Third, another link called "known info needs to dim" was added between the input of the OPC and the input of the OPC's sub-task "Determine IM Actions". With

was made to capture asynchronous communication e.g. through instant messaging apps.

regards to *task delegation*, the tasks were assigned to the entities or agents i.e. the actors, objects, and environment that were found to carry out the specific activities in the system composition as shown in Table 5.1. For instance, "Manage Responder Role" is a task that is delegated to community members as found in the system composition. All the other tasks discussed in this section are associated not only with community members but with all agents representing an actor (Cf. Table 5.1). Figure 5.3 shows the resulting specialization of GAM with respect to its OPC, WIM, and MWI components and for the specific case of a community responder.

The *instantiation* of GAM was carried out by defining domain-specific instances of the of generic information types included in GAM (namely, world information, agent information, agent identification, domain actions, domain agent characteristics). This was carried out by analysing the (a) the system composition, (b) the specialization presented above, and (c) the results of the conceptual framework application through the lens of the generic information types. For example, the conceptual framework application showed that, in the considered system, two types of information are generated by the environment (or world) namely, "shocks" and "announcements" (Cf. Section 5.2). As such, shocks and announcements were introduced as instances of the information type "world info" in GAM (this is the type of information shared and collected by the agents in interaction with other agents and the environment). Additionally, the information type "domain agent characteristics" was instantiated (refined) by assigning state variables and properties to the agents. *States* (or state variables) were introduced when a task required a particular variable to keep track of the dynamic state of an agent e.g. associated with its goals (information needs), condition (e.g. affected by a flood), or roles (responder or not). In other cases, state variables were included to store, receive and share information according to the devised information flows (e.g. in the case of the list of known information needs). *Properties* of the agents were also introduced to account for the static characteristics of the agents necessary to determine how particular tasks were going to be carried out by given agents (e.g. group). Table 5.2 shows the result.

Generic information types from GAM	**Instances for the domain of disaster IM**
World info	Shock, Announcement, Noise[5]
Other agent info	Connections
Other agent identification	N.A.
Domain actions	N.A.
Domain agent characteristics	Known information needs (state), Latent information needs (state), Responder? (state), Affected? (state), IM actions (state), IM focus (state), Group (property), Altruism (property)

Table 5.2: Instantiation of the domain-specific information types from GAM for the community member agent.

Given the agents, their tasks, states, properties, and interactions a model

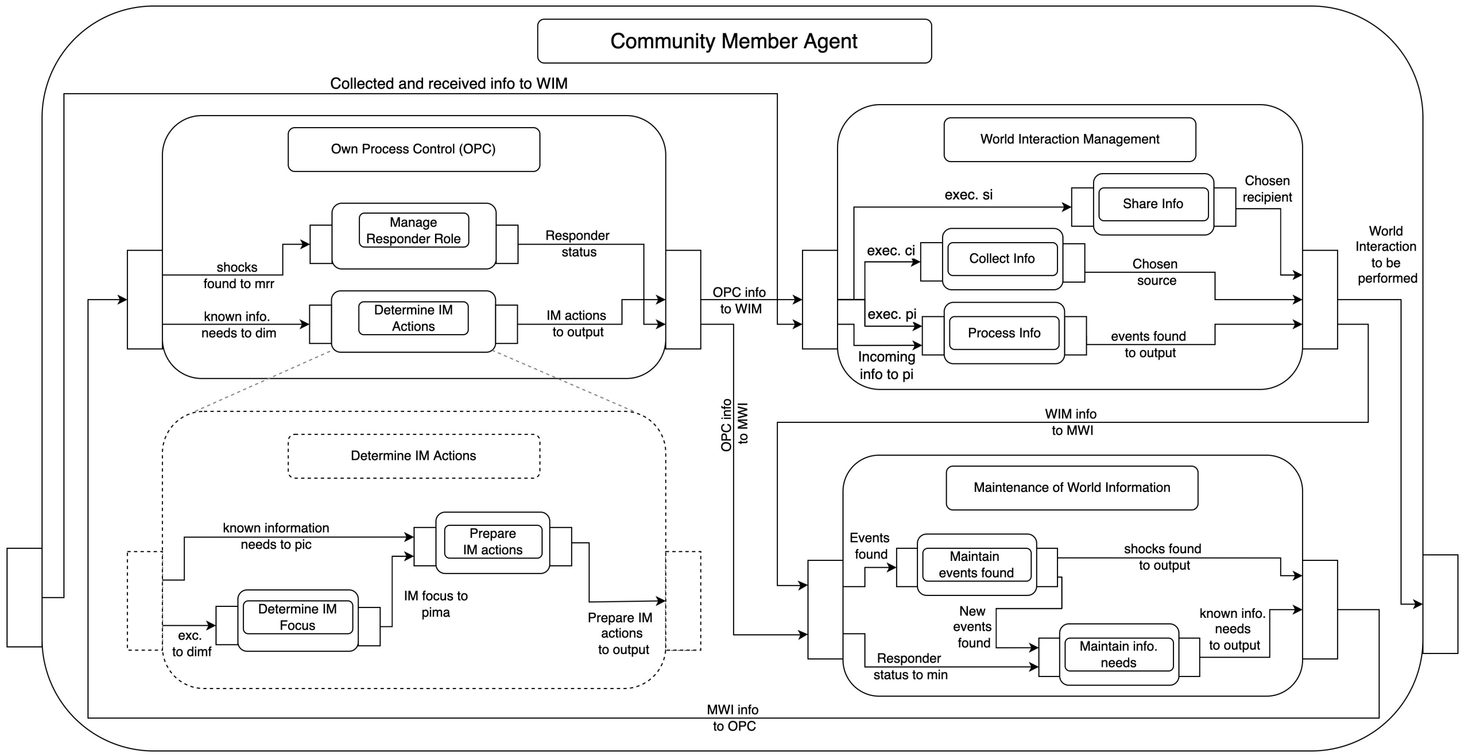

Figure 5.3: Example of tasks specialization for community member agents. The example shown focuses specifically on the specialization of GAM's generic tasks "Own Process Control" (OPC), "World Interaction Management" (WIM), and "Management of World Information" (MWI). In the figure, the dashed line is used to highlight the specialization of the task "Determine IM actions" with the sub-tasks "Determine IM Focus" and "Prepare IM Actions". The full lines in the picture show the links used for information exchange among tasks.

5

conceptualization was built. When the agents had common tasks, properties and states and could therefore be seen as instances of a more abstract entity, a new entity was introduced with the given common tasks, properties and states. Figure 5.4 shows the resulting conceptualization including both the general entities and their instances for the specific case of Marunda.

Then, quantitative data on the number of population per age in the Marunda administrative subdivisions (RT and RWs Cf. Figure 5.1) was used to capture in the model the number of residents that actually live in Marunda and their spatial locations.

Next, to capture the *relevant system's performance* selected in the problem definition (Cf. Section 5.3), the authors developed direct indicators of information quality and specifically of timeliness and relevance to be provided as the model output. These quantitative indicators were designed based on the definitions obtained through qualitative inquiry during the conceptual framework development (Cf. Table 4.3). Developing direct indicators of information quality is a novel approach as the existing ABMs capturing disaster information sharing rely on indirect (or proxy) operational indicators such as the correct and timely allocation of resources to measure information quality [5, 16, 21]. Using direct indicators of information quality has the advantage of allowing to focus on the information sharing challenges at hand while abstracting from the context of a specific operational problem. Additionally, the authors chose to measure the *gap in information relevance and timeliness* rather than relevance and timeliness, as this was found to be a better measure of the on-going performance of the system (or lack thereof) during the response to a disaster. Specifically, information gaps represent the average amount of information needs that the actors were not yet able to address at a given time of simulation. In the case of relevance, this gap is measured without considering when the information needs were addressed. Conversely, the timeliness gap takes into account time and it can only be reduced when the information needs were addressed before their expiration. Given these consideration the indicators for relevance and timeliness gaps were defined as follows.

$$Relevance\ Gap\ (t) = \frac{\sum_{k=1}^{n_{actors}} (info\ needs\ _k\ (t) - info\ needs\ addressed\ _k\ (t))}{n_{actors}} \tag{5.1}$$

$$Timeliness\ Gap\ (t) = \frac{\sum_{k=1}^{n_{actors}} (info\ needs\ _k\ (t) - info\ needs\ addressed\ on\ time\ _k\ (t))}{n_{actors}} \tag{5.2}$$

Where:

- n_{actors} = total number of actors in the simulation;
- $info\ needs\ _k\ (t)$ = total information needs received by the actor k at the simulation time (t)

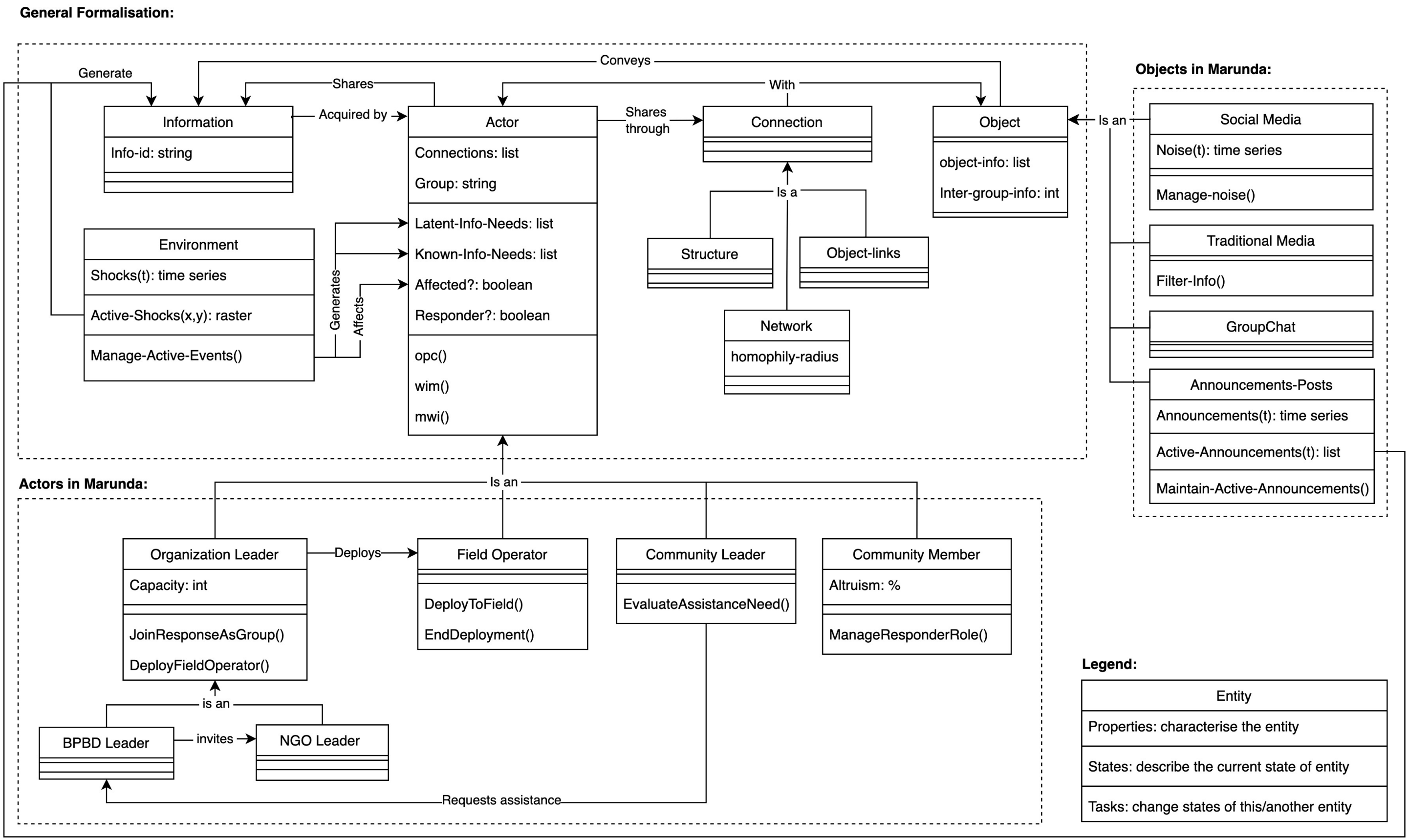

Figure 5.4: Concept Formalization: description of entities, their properties, states and tasks in ACDIS both in general and for the case study of Marunda. Among these entities, the actors, objects and environment are agents.

- *info needs addressed* $_k$ (t) = total information needs addressed for the actor k at the simulation time (t)
- *info needs addressed on time* $_k$ (t) = total information needs addressed before their expiration for the actor k at the simulation time (t)

From this definition it follows that the timeliness gap is always higher than or equal to the relevance gap. This is due to the fact that the number of information needs addressed on time "*info needs addressed on time* $_k$ (t)" is always less or equal to the information needs owned by the actor "*info needs addressed* $_k$ (t)". The timeliness and relevance gap indicators were computed as a total and with specific reference to known and latent information needs as discussed in the section "Conceptual Framework Application".

Model Narrative Development:

Starting from the general conceptualization and the conceptual framework application (specifically the analysis of system's change and performance Section 5.2) from the previous steps, a narrative was developed by specializing the task control knowledge and instantiating the knowledge bases included in GAM. In the following, the narrative development is illustrated through the example of the OPC and one of its sub-task "Determine IM actions" as shown in Section 5.5.

First, **task control knowledge** was specialized for each of the tasks introduced in the model conceptualization that have sub-tasks (Cf. Appendix A). This included for instance the OPC with its sub-tasks manage_responder_Role and determine_IM_actions. Task control knowledge had to be provided also for determine_IM_actions to manage the execution of its sub-tasks determine_IM_focus and prepare_IM_actions (Cf. figure 5.3). In the case of the OPC, task control knowledge was specialized as in the following.

```
if start
then next—component—state (determine_IM_actions, awake)
and next—target—set (determine_IM_actions, IM_actions)
```

The above means that if the OPC is started by the task control knowledge of the community member agent, the sub-task determine_IM_actions is activated with the target (or goal) to provide the IM_actions as its output. Similarly, also the manage_responder_role task is managed by the task control knowledge of the OPC, as shown in the following.

```
if start
then next—component—state (manage_responder_role, awake)
and next—target—set (manage_responder_role, responder?)
```

In the above, it can be noticed how the information type "responder?" obtained through instantiation of GAM in Section 5.5 is used by the task control knowledge of the OPC to set a target for the sub-task become_responder.

Next, the task control knowledge of the the task "determine IM actions" was specialized as in the following.

5

```
if start
then next–component–state (determine_IM_focus, awake)
and next–target–set (determine_IM_focus, IM_focus)
```

The above determines that when the determine_IM_actions task is awakened by the task control knowledge of its parent task (the OPC), the sub-task determine_IM_focus is awakened with the target of producing the information management focus as its output.

```
if evaluation (determine_IM_focus, IM_focus, succeeded)
then next_component_state (prepare_IM_actions, active)
and next–target–set (prepare_IM_actions, IM_actions)
and next_link_state (IM_focus_to_pima, awake)
```

The task control knowledge shown above determines that, once the determine_IM_focus task succeeded in its target, the prepare_IM_actions task is awakened with the target of providing the IM_actions as its output. It must be noted that the IM_actions are transferred from the task determine_IM_focus to the task prepare_IM_actions via the link IM_focus_to_pima. Such information exchange is possible given the link is awakened by the task control knowledge (see the "next_link_state" statement above).

Second, **knowledge bases** were instantiated for each of the tasks that do not have sub-tasks. Task control knowledge looks at the sub-tasks of a task as black boxes that need to be managed based solely on their inputs and outputs. Knowledge bases define the rules implemented within a task once it is activated by the task control knowledge. Specifically, the knowledge bases define the way a task's output information is obtained given the input information (if any). Knowledge bases were instantiated based on the concept formalization and on the results of the analyses of system's change and performance (Cf. Section 5.2). For example, the knowledge base used by the task Prepare_IM_actions was defined based on the analysis of system's performance. Two distinct types of information needs, namely latent and known information needs were found (Cf. analysis of system's performance in Section 5.2). These two types of information needs present implications not only for the performance of the system, but also for the information collection behaviour of the actors. Specifically, actors can collect information only when they have information needs of which they are aware i.e. when they have know information needs. As such, the knowledge base for the task Prepare_IM_actions enables the actors to collect information only when their list of known information needs is not empty. This knowledge base is defined as in the following.

```
if (IM_focus, collect)
    if not (known_info_needs_list, empty)
    then (IM_actions, collect)
    if (known_info_needs_list, empty)
    then (IM_actions, process)

if (IM_focus, process)
```

```
then (IM_actions, process)
```

The knowledge base above specifies that when the IM_focus obtained through the determine_IM_focus task is that of collecting information, then two options are available. If the agent's list of known information needs is not empty, then the agent proceeds to collect information by setting the IM_actions information type to "collect". However, if the list of known information needs is empty, then the agent proceeds to process the received information by setting IM_actions to "process". Additionally, when the IM_focus obtained through the determine_IM_focus task is that of "processing", the agent will again proceed to process the received information by setting IM_actions to "process".

Next, a **narrative was assembled**. Firstly, the task control knowledge informed the order of execution of the tasks in the narrative. Starting from the most abstracted tasks and gradually proceeding to their sub-tasks, it was possible to delineate the sequences of tasks triggered by particular events or activation conditions (Cf. "Task control knowledge" in Appendix A). However, it must be noted that the occurrence of task-triggering events was not known. The order of occurrence of task-triggering events was a deliberate choice of the modeller. For the case of a community member agent, the most abstracted tasks were the OPC, WIM and MWI. Among these, MWI was chosen as the initial task. MWI, and specifically its sub-task maintenance_of_information_needs, is triggered every pre-defined amount of time[6] to check whether a new shock or announcement is generated by the environment, and possibly add an information need when such an event is relevant for the considered actor. Next, the actor determines what kind of information management activities to execute through the OPC's sub-task determine_IM_actions (and its sub-tasks determine_IM_focus and prepare_IM_activities). The task determine_IM_focus chooses whether to collect new information or process the received information. Then, determine_IM_actions assesses whether the actor has known information needs before proceeding to collect information, or proceeds to process the received information otherwise. Once the agent has collected or processed information, the agent proceeds to share information. The knowledge bases provide the rules executed by the most elementary tasks (i.e. those that do not have sub-tasks). The resulting narrative for the considered example of a community member agent is shown in figure 5.5.

5.6. Software Implementation:

The model was implemented in NetLogo 6.1.1 as this modelling environment provides the means to implement reasonably complex models with a relatively low time investment required for the software implementation [22]. Figure 5.6 shows part of the GUI of the resulting implementation. Appendix B illustrates the ODD description of this model. *Additionally, the peer-reviewed source code, input data, and its description based on the ODD protocol [23–25] can be found on the COMSES Net Computational Model Library* at **this link** [26].

[6] This is another deliberate choice of the modeller. It could be executed e.g. at every time step.

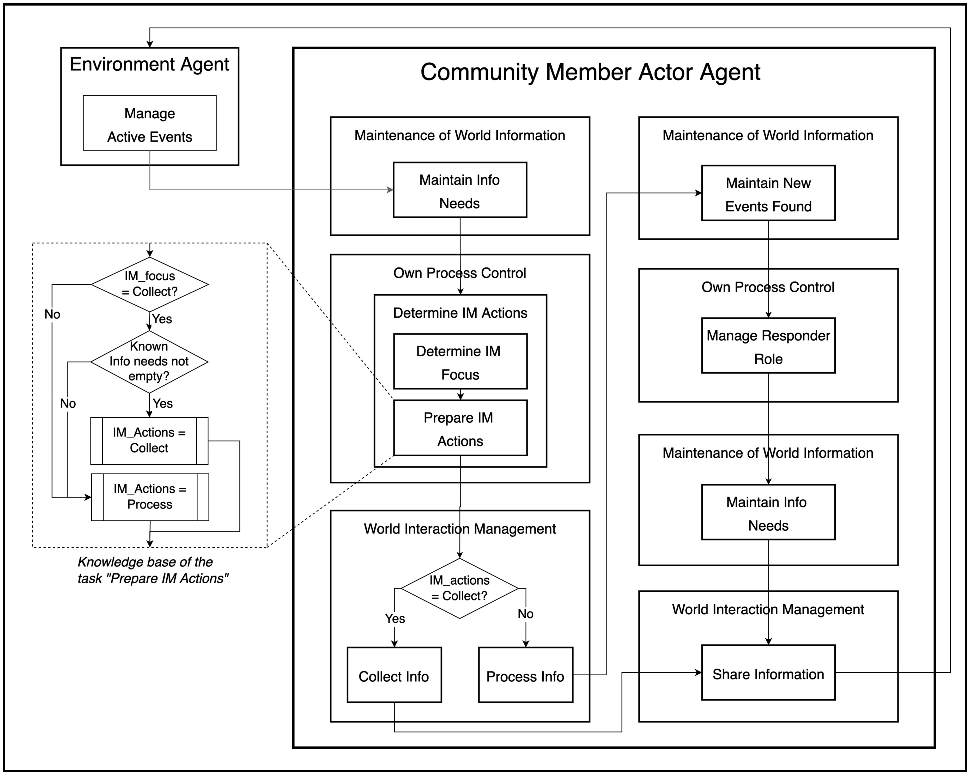

Figure 5.5: Developing a Model Narrative: narrative for the community member actor agent developed based on the model conceptualization, the specialization of the task control knowledge, and on the instantiation of the knowledge bases included in the generic model GAM. In the figure, the task control knowledge is represented by the order of execution of the tasks shown by the full arrows. An example of a knowledge base is also illustrated for the task "prepare IM Actions" through dashed lines.

Model Evaluation:

The empirical model was verified thoroughly through single agent, interaction, and multi-agent testing as suggested in [27]. To provide an example of multi-agent testing the model was run a total of 1215 times considering different scenarios of environmental turbulence. Environmental turbulence was conceptualized as the amount of shocks and announcements occurring during one day of simulation (Cf. Section 5.4). The results of the data analysis are shown in the following. In all figures below, the confidence levels were calculated via bootstrapping.

Firstly, it can be noticed that the information gaps associated with both timeliness and relevance tend to increase over time (see Figure 5.7). This shows that, while the number of information needs grows due to the occurrence of more

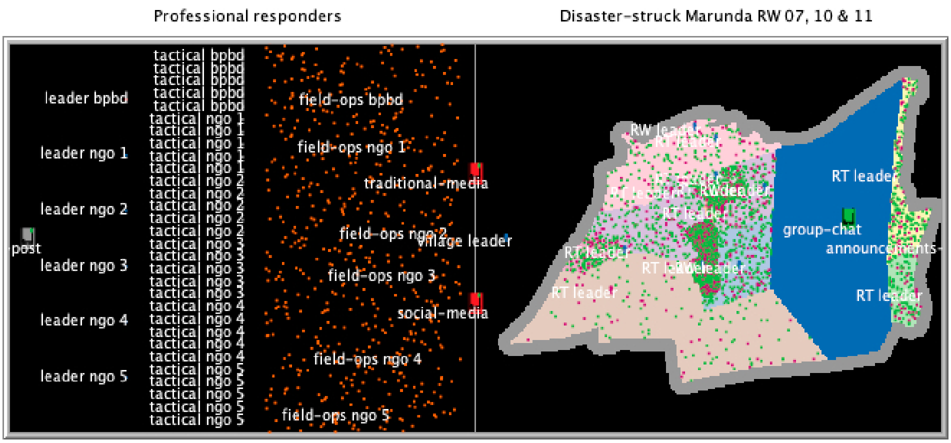

Figure 5.6: GUI resulting from the software implementation of the concept formalization and narrative.

disruptive events (shocks and announcements), the actors are not receiving all the information they need, leading to the cumulation of information gaps. However, it can also be observed that in some cases (e.g. after 10 hours of simulation) the gap is being reduced as the actors' information needs are being addressed at a rate that's higher compared to the increase in information needs due to new disruptive events.

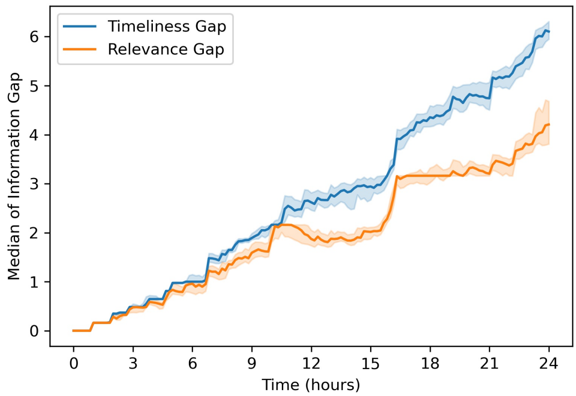

Figure 5.7: Comparison between the median of the timeliness and relevance information gaps at each time step across all simulations. The vertical axis represents the number of pieces of information that the actors still need on average.

Secondly, the data analysis confirmed that, as follows from definition, the median of the timeliness gap is always equal or above that of the relevance gap (Cf. Section 5.5). Further, at some point of the simulation the information needs of the actors start to expire. When this occurs, it becomes possible for the actors to address their information needs not on time. As such, the value of "$\textit{info needs addressed on time}_k\ (t)$" in equation (2) becomes smaller than "$\textit{info needs addressed}_k\ (t)$" in equation (1), leading to an increase of the timeliness gap compared to the relevance gap and thus to their divergence as shown in figure 5.7. For the same reason, it can be observed that in some cases the relevance gap is reduced to a greater extent compared to the timeliness gap.

Further, the data analysis demonstrated that both the number of shocks per day and announcements per day contribute to increasing the cumulative relevance and timeliness gaps (see Figure 5.8). These results confirm the expectation that higher levels of environmental turbulence (i.e. more things to keep track of) make it more difficult for the actors to address their information needs and thus reduce the information gaps. It can also be observed that the confidence intervals around the median are much wider at specific points of the simulation compared to others. This uncertainty in the median can be attributed to the stochasticity used to (a) initialize the model's the structures and networks (connections Cf. figure 5.4), and (b) make the agents choose which other agents to collect information from and share information to. The fact that this uncertainty varies over the simulation is a consequence of the model structure. Specifically, it is only after a given disruptive event is released, that information needs are assigned to the actors, which on turn increases the information gaps. How rapidly (if at all) the associated information needs are addressed will depend on the connections available and on how effective the random chains of information exchange across the actors turn out to be.

Additionally, latent and known information needs were compared in terms of the associated relevance and timeliness gaps. The results show that information gaps associated with latent information needs have medians higher than those of known information needs (see Figure 5.9). Such a system's performance is also consistent with the authors' expectations that latent information needs are more difficult to address as the actors are not aware of them and therefore cannot actively search for the related information (Cf. analysis of system's performance in Section 5.2). Figure 5.9 also shows that the difference between information gaps associated with latent and known information needs is particularly pronounced for the timeliness gap. This behaviour is exemplified by the information gaps for latent needs occurring after 18 hours of simulation. The relevance gap peaks and then start decreasing, while the timeliness gap simply keeps growing. This suggests that the impact of being unaware of the information needed affects more heavily the ability of actors to get such information on time, rather than simply receiving it at any time.

Finally, the extent to which communities and professionals address their information needs was examined for both relevance and timeliness gaps. The results in Figure 5.10 show that communities address a larger portion of their information needs, resulting in consistently lower information gaps than those of professionals for both relevance and timeliness. Moreover, the difference between

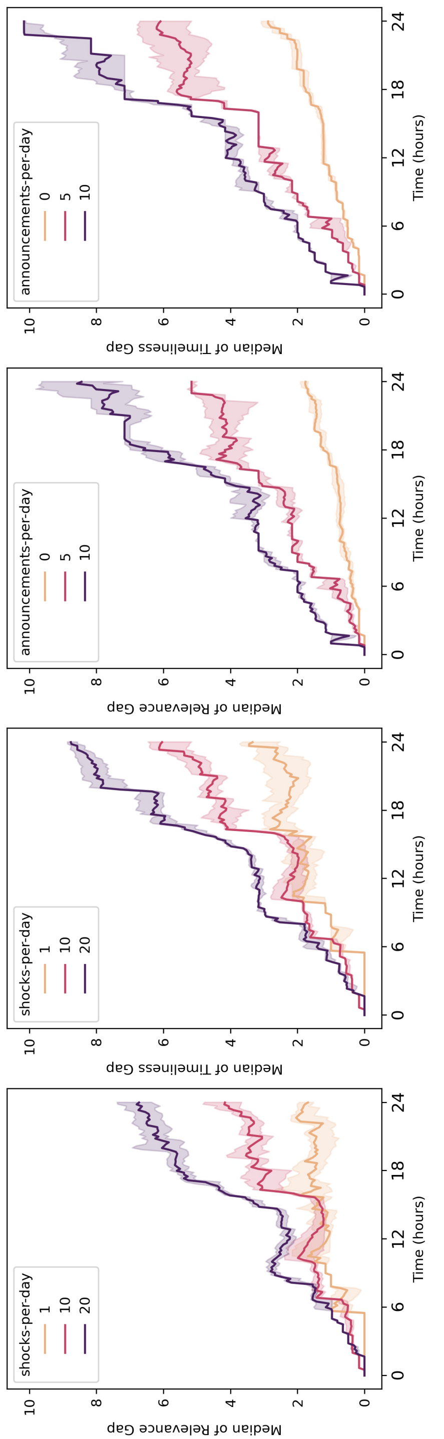

Figure 5.8: Median of Relevance and Timeliness Gaps for different levels of environmental turbulence (shocks per day and announcements per day).

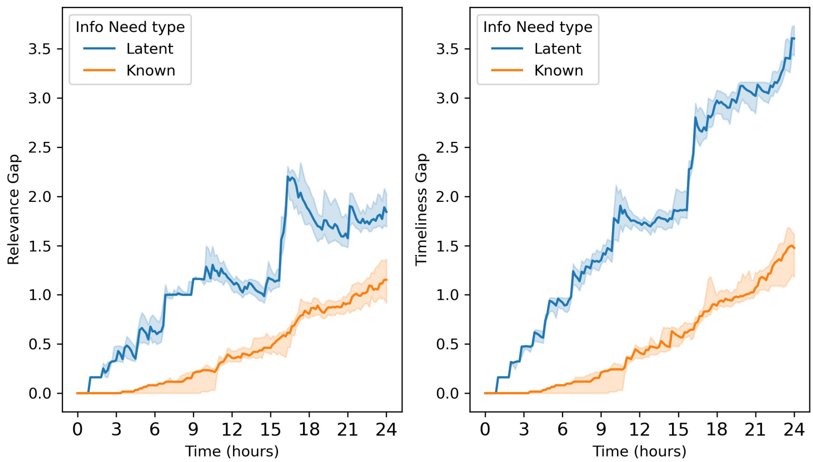

Figure 5.9: Comparison between the median of information gaps for latent and known information needs. The figure shows such a comparison for both the relevance gap (left figure) and the timeliness gap (right figure).

professionals and communities is more pronounced for the timeliness gap than for the relevance gap (Cf. Figure 5.10, right and left panels, respectively). This indicates that communities not only fulfil a larger share of their information needs but also do so in a more timely manner compared to professionals, enabling them to maintain a much lower timeliness gap. This observation is further supported by the minimal difference in communities' relevance and timeliness gaps, suggesting that they meet most of their information needs on time. In contrast, professionals exhibit a significantly larger timeliness gap than relevance gap, highlighting that they address fewer information needs overall and in a less timely manner than communities.

The justification and evaluation of a model—through verification, calibration, and validation—depend on its intended purpose [12]. As a descriptive model, the one developed in this study aims to formalise and integrate insights from the considered case study with existing theory on crisis information management. Accordingly, the model's structure was specified to reflect both empirical findings and theoretical foundations. Evaluation involves (1) confirming that simulations with the model produce the theoretically expected behaviour (verification); (2) ensuring that the model's structure can reproduce observed macro-level patterns in terms of the system's behaviour and performance (calibration); and (3) assessing—using independent data not employed during model specification or calibration—whether the model's structure and the behavioural patterns it reproduces align with the real-world system it aims to represent (structural and behavioural validation, respectively) [28].

The results illustrated in Figures 5.7, 5.8, and 5.9, along with their accompanying discussion, demonstrate that the model has been verified and calibrated.

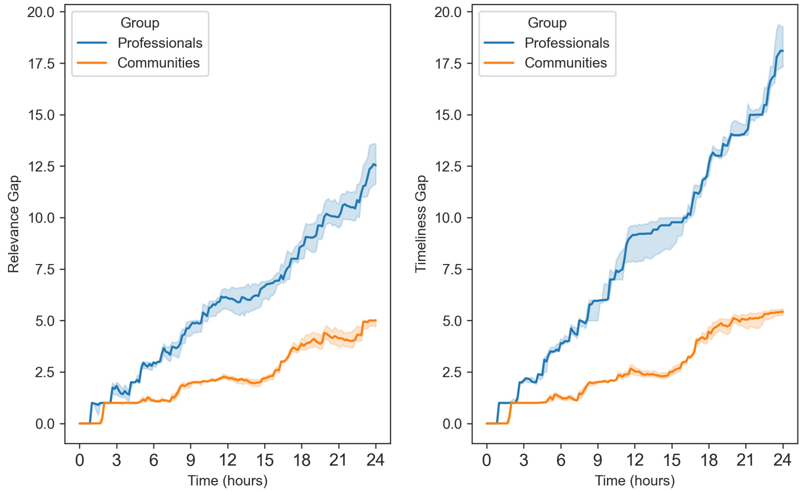

Figure 5.10: Comparison between the median of information gaps for professionals and communities for both the relevance gap (left figure) and the timeliness gap (right figure).

Regarding verification, Figure 5.7 shows that the timeliness gap is consistently equal to or greater than the relevance gap, as expected based on the definitions of these gaps (Cf. this section below Equations 5.1 and 5.2). Additionally, Figure 5.8 shows that under conditions of increased environmental turbulence, both the relevance and timeliness information gaps increase. This finding aligns with the theoretical expectation that a higher frequency of new information introduced into the system makes it more difficult to deliver such information to those who need it, thereby increasing the information gaps. In sum, the model is considered verified as it reproduces theoretically expected behaviour in terms of information relevance and timeliness at varying levels of environmental turbulence.

With respect to calibration, Figure 5.7 shows that the simulated results reflect the empirical finding that the relevance and timeliness of information are not satisfactory—that is, the relevance and timeliness gaps are not adequately addressed—particularly in the case of timeliness (Cf. Section 5.2). Furthermore, Figure 5.9 illustrates that information gaps are greater in the case of unknown information needs, another finding from the data analysis (Cf. Section 5.2). As such, the model can be considered calibrated, as it reproduces the observed system-level patterns in information relevance and timeliness and known and unknown information needs.

Structural and behavioural validation have not yet been conducted in this study; these will be addressed in future work. Structural validation will aim to ensure that the model's conceptualisation and narrative align with how information is actually managed at the micro level in the case study. This will involve discussing the model's structure and assumptions with members of the Marunda community, as well as with representatives of other organisations included in the model. Behavioural validation will aim to confirm the observed patterns regarding information relevance and timeliness, ensuring that the patterns reproduced in the model reflect those occurring in reality. To this end, new data on information relevance and timeliness will be collected from the Marunda community and professional response organisations operating in Jakarta focusing on new flooding events that occurred after the original case study data collection period (2018).

5.7. Iterative conceptual framework development:

In the model development phase a new system characteristic was found, namely that of "Objects". Objects represent non-human (technological) entities that can support the actors belonging to one or more groups in their information sharing and coordination activities. Given this definition obtained through the conceptual framework application (Cf. Section 5.2), the following relationships are found between objects and other system's characteristics. Activities can be carried out *through* objects. Additionally, objects *connect* the actors within a group and also actors that belong to different groups so that they can exchange information and coordinate. The objects and their relationships with the system's characteristics "Activities" and "Groups" were integrated in the conceptual framework as shown in figure 5.11. This updated conceptual framework can be used in substitution of the one developed in Chapter 4 (fig. 4.1).

5

5.8. Discussion

This chapter addresses both (a) RQ2 by developing an ABM for studying ACDIS across groups and (b) RQ3 by demonstrating the second phase of the methodology introduced in Chapter 3 and discussing the overall methodology's rigour, ability to balance comparability and flexibility, and versatility (Cf. Table 1.1). The following sections discuss how the chapter addresses these research questions.

5.8.1. Developing an ABM of ACDIS

This chapter aimed to address RQ2 by developing an ABM for supporting the study of actor-centred disaster information exchange among different groups and specifically between professional response organisations and communities. This model takes an actor-centred perspective to disaster information sharing across groups by considering the impact of micro-level behaviour of the actors on information exchange between communities and professional response organisations, as discussed below. At the micro level, the model incorporates individual factors such as the actors' shifting roles in response to changes in their environment, which affect the actors' information needs. For example, community members may decide to become responders upon learning of the disaster's occurrence. When they do, they begin to require information about shocks (Cf. Appendix B, Section 8.1). Another micro-level factor is the type of information needs (i.e., latent or

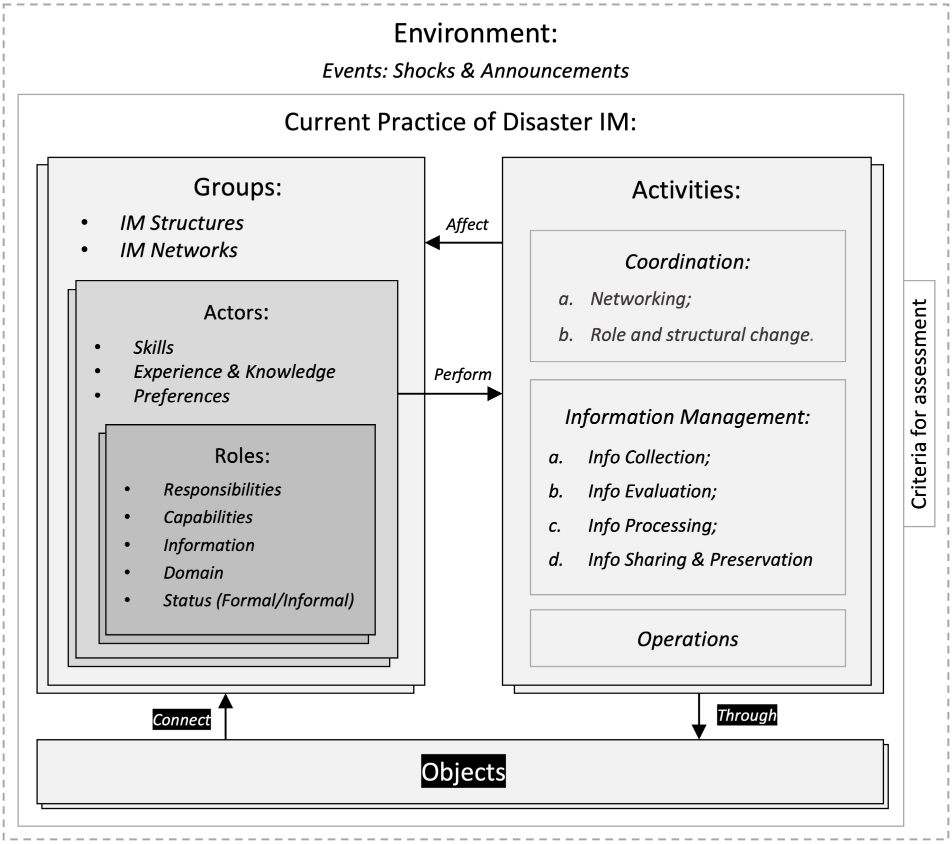

Figure 5.11: Updated conceptual framework with the new systems characteristics and relationships (highlighted in the figure).

known), which significantly influences actors' information-sharing behaviour. This is because actors can actively seek information only when they are aware of their needs — that is, when these needs are known rather than latent (Cf. Section 5.5).

This model studies the impact of these micro-level factors on inter-group information exchange. The two groups - i.e., communities and professional response organisations - have access to mutually relevant information that they need to exchange to meet their information needs. Specifically, professionals have direct access to announcements needed by communities, while communities have more direct access to shocks (occurring in the disaster-affected area where the community is located), which are needed by professionals (Cf. Appendix B). For effective information exchange, these groups must share information about shocks and announcements; that is, a two-way communication must be established between communities and professional response organisations to ensure both groups can address their information needs. The effectiveness of inter-group information exchange is measured by the information gaps of the actors — i.e., the extent to which their information needs remain unmet at a given point in the simulation. The smaller the information gaps, the greater the system's ability to meet information needs and thereby provide effective inter-group information exchange.

The findings from simulations with this model provided an actor-centred insight into the impact of micro-level behaviour on disaster information sharing across professionals and communities. Specifically, the presence of latent information needs at the micro level shapes the information collection behaviour of actors, as they cannot actively seek information if they are unaware of their needs. This micro-level characteristic results in higher information gaps for information associated with latent needs (particularly in terms of timeliness) compared to needs that actors are aware of. This finding is actor-centred, as it emerges from the micro-level types of information needs and the associated information-sharing behaviours, which in turn affect information exchange across groups, as shown by the difference in information gaps associated with the two types of needs.

In sum, this chapter developed an ABM that provided the means to study of disaster information sharing across different groups (specifically communities and professional response organisations) from an actor-centred perspective, providing insights into disaster information sharing. In doing so, this chapter addressed RQ2.

Although their impact on inter-group information exchange is not assessed in this chapter, the model developed also considers factors at the meso and macro levels. At the meso level, the model incorporates group-specific characteristics, such as hierarchical structures and scale-free social networks used for information exchange within groups (Cf. Figure 5.1 and Appendix B, Section 6). At the macro level, the model includes vertical information-sharing structures between communities and governmental disaster management organisations, reflecting the institutional settings and networked interactions within which groups operate (Cf. Figure 5.1 and Appendix B, Section 6). Another macro level factor considered in the model is the level of environmental turbulence (associated with environmental volatility, Cf. Chapter 6).

Studying the interplay between micro-level behaviour and these meso- and macro-level factors, as well as the resulting impact on inter-group information exchange, offers avenues for further research in actor-centred disaster information exchange across groups. First, findings from this chapter show that higher environmental turbulence hinders actors' ability to meet information needs and maintain low information gaps. This is likely due to the actor's bounded rationality, i.e., limited capacity to process information. Future research will investigate how bounded rationality at the micro level interact with increasing levels of environmental turbulence and volatility at the macro level to impact inter-group information exchange. Second, future research could also focus on explaining from an actor-centred perspective another finding obtained in this chapter, which shows that communities address more of their information needs in a timely manner compared to professionals. This explanation may stem from the interplay among micro, meso, and macro-level factors represented in the descriptive ABM developed in this chapter. For example, at the meso level, network characteristics differ among the two groups: the Marunda community relies on a centralized WhatsApp group that connects nearly all members, enabling more efficient information flow. In contrast, professional responders lack a similarly centralized structure, which may hinder coordination. At the micro level, information needs also differ: while all professional responders require both announcement- and shock-related information, only a subset of community members assume responder roles and need information about shocks, whereas the majority require only announcement-related information. Consequently, the overall information needs within the community are lower, making it easier for them to meet their needs on average.

5.8.2. Methodology for developing ABMs of a phenomenon of interest

This section discusses how the findings from Chapters 4 and 5 (this chapter) address RQ3. Specifically the findings of these two chapters address RQ3 as they show that the methodology introduced in Chapter 3 provides the means to (a) strike a balance between the comparability of framework-based methodologies and the flexibility of case-based methodologies while maintaining rigour and (b) to provide versatility by enabling to develop ABMs with both theoretical and empirical purposes. The methodology is structured in two phases. In the first phase, a conceptual framework centred on a specific phenomenon of interest is designed based on literature and the findings from one or more case studies. In the second phase, the conceptual framework together with generic models are used to guide the development of an ABM for studying the phenomenon interest.

The two-phase methodology was illustrated through a case study of Jakarta (Indonesia), focusing on ACDIS as the phenomenon of interest. Chapter 4 demonstrated the first phase of the methodology, showing that it enabled the development of a conceptual framework for the phenomenon of interest (Cf. Section 4.6).

Second, this chapter (Chapter 5) illustrated the second phase of the methodology. The conceptual framework developed in Chapter 4 was applied to the case study of Jakarta to carry out the analyses of system's configuration, change, and performance based on the qualitative data collected via interviews and focus groups and presented in Chapter 4. These analyses were instrumental in the development of a conceptual model (the system's composition) capturing the agents, their interactions and performance in the Marunda community (i.e. the current practice of disaster information sharing) that are key for the considered phenomenon. Next, the Generic Agent Model (GAM) was chosen given that other more specialized generic models such as GCAM were not suited for the considered phenomenon of ACDIS. GAM was used to structure and interpret the results of the conceptual framework application, and the system composition to design the internal processes driving the agents' interactions. This process, called specialization and instantiation, enabled the formalization of the system composition in a software-implementable manner (or model concept formalization) and the development of a model narrative (or model narrative development), resulting in an empirical descriptive ABM. Finally, during model development new systems characteristics and relationships were found. These were integrated in the conceptual framework for future use.

The case study showed how the proposed methodology enabled the translation of qualitative data into an empirical ABM by balancing comparability and flexibility while maintaining rigour. Firstly, the methodology enabled to retain some degree of *comparability* with future studies by developing and centring the model development process on a conceptual framework tailored to the phenomenon of ACDIS. Such a conceptual framework provides a clear mission, categories of meaning, and criteria for the assessment of performance so that future simulation studies focusing on ACDIS will be able to interpret and build upon the results of this study through the same conceptual framework. However, while future simulation studies focusing on the same phenomenon will be able to rely on the same conceptual framework, these studies may potentially choose different generic models compared to the one used here (GAM). As such, comparability with future studies was retained only to a certain degree. Other methodologies such as [29] that fully rely on the same framework across different studies (framework-based) provide a greater level of comparability. However, this comparability comes at the cost of flexibility i.e. the researchers are not able to choose among different agent theories or architectures that e.g. are adequate for the particular phenomenon considered.

Secondly, the proposed methodology provided some degree of *flexibility*. Firstly, the methodology enabled to capture a novel phenomenon of interest (ACDIS) for which an adequate conceptual framework was not initially available (Cf. Chapter 4, Section 4.6). Secondly, the methodology provided the means to choose a generic model capturing a particular agent architecture that was suited to the considered phenomenon of interest and modelling purpose (this chapter). However, flexibility was provided only to a degree as the model development process was constrained by the use of the conceptual framework developed in the first phase of the methodology. Methodologies that tailor an ABM to a particular case without relying on a common framework (case-based) as in [30] provide a higher degree of flexibility in that they can capture the nuances and details that characterize a particular case study without being limited by the availability and constraint of pre-existing frameworks or agent architectures. However, such methodologies are not designed to retain common ground that can be used to compare the results of different case studies focusing on the same phenomenon.

Thirdly, the proposed methodology enabled to maintain rigour by systematically (a) developing a conceptual framework for the considered phenomenon of interest (Cf. Chapter 4, Section 4.6) and (b) structuring and interpreting qualitative data through the lens of two frameworks [31], namely the conceptual framework developed in Chapter 4 and the GAM generic model (this chapter).

In sum, while the methodology proposed in this article does not provide the same degree of flexibility of case-based methodologies, nor the same level of comparability provided by framework-based methodologies, it enables to provide both flexibility and comparability to a certain degree, thus striking a balance between them while maintaining rigour. Such a balance is obtained by providing some standards (the conceptual framework developed to capture a particular phenomenon of interest and the use of generic models) but not too many (i.e. the researchers can choose different generic models for the same phenomenon of interest).

With regards to *versatility*, the process of designing policies supported by ABMs may involve the development and use of a series of models with different theoretical and empirical purposes [12]. In this chapter, an empirical ABM with a descriptive purpose was developed which is meant to capture and formalize the knowledge gathered on the current practice of disaster information sharing in the Marunda Community of North Jakarta. Based on this model, another empirical model with an explanatory purpose could be developed at a later stage to support the study of ACDIS (Cf. Section 5.8.1). Theoretical models may also be needed e.g. with the purpose of illustrating the implications of given information sharing strategies in an abstract system prior to testing them empirically. While a theoretical model was not developed in this chapter, the proposed methodology provides indications for such a model to be designed via the conceptual framework obtained in phase 1 and generic models. Specifically, instead of being used as tools to structure and interpret qualitative information, the conceptual framework and generic models provide templates for the design of the agents, their interactions, performance, and internal processes. As such, the proposed methodology is versatile as it enables to develop both theoretical and empirical ABMs [12] for studying a given phenomenon of interest.

The proposed methodology presents the following implications for the development of ABMs for studying a phenomenon of interest through qualitative inquiry. Firstly, the methodology enables to uncouple the analysis of the system including the key agents, their activities, and interactions (captured through the system composition) from the analysis of the agent's internal processes and behaviours that drive their activities and interactions (captured through generic models). As such, via this methodology, researchers can rigorously interpret the same system composition through the lens of different generic models representing e.g. different agent architectures. This can enable for instance to systematically develop a series of comparable ABMs for the same case each including a different agent architecture. A potential application could be testing alternative (or rival) explanations for a particular system's change or performance of interest that is relevant for the phenomenon under study (as in [6]). Secondly, in the absence of other more refined generic models that are suited to the considered phenomenon of interest, the researchers can rely on the Generic Agent Model [18]. GAM only assumes general features that characterize an agent [32, 33], and as such it can be widely applied to different phenomena.

Further, when a generic model is used in the model concept formalization and narrative development, additional tasks and knowledge structures may be introduced that can be abstracted to develop a new generic model tailored to the considered phenomenon of interest [19]. Such an abstraction process requires additional effort from the researchers. However, it has the advantage that future studies focusing on the same phenomenon are able to rely on a generic model that is refined for the considered phenomenon (instead of e.g. using GAM).

Finally, according to the proposed methodology not only empirical but also theoretical models are developed on the basis of a conceptual framework that is designed empirically (through qualitative inquiry). Then, while theoretical models are not specific with respect to any case study [12], those developed with this methodology still reflect empirically-embedded system's characteristics, attributes, relationships and criteria for assessment of performance that are relevant for the considered phenomenon and are captured in the conceptual framework. While the findings of these theoretical models e.g. hypotheses regarding the effectiveness of particular policies still require to be tested empirically, these models are more likely to reflect issues that are relevant for phenomenon of interest compared to models developed through conceptual frameworks that are designed in a purely inductive manner.

Despite its advantages, the methodology introduced in this article presents limitations providing ground for further research. Firstly, the proposed methodology requires a considerable investment in time and resources required to develop a novel conceptual framework and possibly a new generic model before actually developing a model.

Secondly, the proposed methodology focuses solely on the use of qualitative inquiry. However, combining the current qualitative approach with quantitative research methodologies provides an opportunity for enhanced rigour in the development of empirical models [30, 34]. For instance, the model conceptualization and narratives designed through the use of generic models could inform the design of quantitative research tools (e.g. surveys) that aim at capturing the choices made by the actors statistically.

Further, in the context of empirical models, the methodology does not offer a concise way to trace which qualitative sources of evidence support specific model development choices. This limitation is particularly relevant when writing scientific papers, where space to present such evidence is often constrained. To address this, future research could explore integrating the findings generated at various stages of the methodology with the RAT-RS protocol introduced by Achter et al. [35].

Additionally, this methodology prescribes to begin the model development process with a conceptual framework that incorporates numerous factors and relationships. This carries the risk of introducing excessive detail, which can hinder the model's utility for research purposes. As noted by [12], it is essential to choose the level of detail and complexity carefully, aligning it with the model's intended purpose. For instance, in a descriptive model, capturing the nuances of the specific case under study is important. Conversely, in a theoretical model aimed at illustrating a particular concept or emergent mechanism, simplicity is often more effective to ensure clarity and focus on the core dynamics. Given that the methodology proposed in this study does not provide detailed guidance on the appropriate level of detail to include at each stage of the model development process—from system identification and composition to software implementation—future research should aim to address this gap.

Next, generic models such as GAM are primarily developed to standardize and facilitate the programming of multi-agent systems, rather than to specifically represent human behaviour. Previous studies have shown that GAM can be extended using established theoretical frameworks relevant to the study of human behaviour (e.g., normative theories), illustrating the potential of this approach to capture the complexity of human behaviour [18]. Nonetheless, a more thorough investigation of the ability of such models to capture human behaviour must be critically assessed through further research.

Finally, while this study has demonstrated how the proposed methodology can lay the groundwork for achieving a degree of comparability with future research—by developing and centring the model development process around a conceptual framework tailored to ACDIS—a true test of comparability can only occur when at least two case studies are conducted using this methodology. This was not possible in the current research, as only one case study was undertaken. Ensuring comparability requires the consistent application of the same theoretical foundations across cases—both in terms of inter-agent interactions captured in the conceptual framework and intra-agent processes embedded in the generic model used. In qualitative research, this also depends on researchers interpreting these frameworks in a consistent manner. While such consistency is easier to maintain when a single researcher conducts all case studies, it becomes more challenging when multiple researchers are involved. To address this, comparison must include a careful examination of how categories of meaning are interpreted by different researchers within both the conceptual framework and the generic model. Alignment of key concepts at both the conceptual and computational levels is essential. This involves systematically comparing categories of meaning during system identification and composition, concept formalization, and the construction of the model narrative. Finally, comparability can also be assessed empirically by configuring computational models developed for different cases to simulate the same conditions and evaluating whether they yield similar outcomes, at least in qualitative terms.

5.9. Conclusions

This chapter addressed a gap in the literature and answered RQ2 by developing an agent-based model (ABM) to study information sharing between professional response organisations and communities during disasters from an actor-centred perspective. Additionally, together with Chapter 4, this chapter answered RQ3 by illustrating the flexibility, comparability, and rigour of the methodology introduced in Chapter 3 (Cf. Table 1.1).

First, regarding the ABM developed and this chapter and RQ2, the findings demonstrate that this ABM effectively facilitated the study of information exchange among different groups from an actor-centred perspective. Specifically, the results indicate that addressing latent information needs (i.e., information needs of which actors are not aware) proved more challenging than addressing known needs, leading to the accumulation of higher information gaps. This occurs because, in the case of latent information needs, actors cannot seek information they do not realize they require. These findings are actor-centred, showing how micro-level factors, such as the type of information needs, affect inter-group information sharing between different groups (specifically communities and professional response organisations). Thus, the ABM developed in this chapter provided the means means to study and gain insights into disaster information sharing between different groups through an actor-centred lens, thereby addressing RQ2. Avenues for future research include (a) examining the interplay of bounded rationality with environmental volatility in sharping inter-group information exchange and (b) investigating why communities may be more successful than professionals in addressing their information needs through an actor-centred perspective.

Second, with respect to the methodology and RQ3, this chapter adds to the findings from Chapter 4 regarding the first phase of the methodology, by illustrating the second phase of the methodology. Chapter 4 showed that the *first phase of the methodology* enabled to rigorously develop a conceptual framework for the phenomenon of interest (actor-centred information sharing). It also provided the flexibility to develop a novel conceptual framework when it was not available for the considered phenomenon of interest.

This chapter (Chapter 5) showed that, through the *second phase phase of the methodology*, qualitative data was systematically structured and interpreted through the lenses of the conceptual framework developed in Chapter 4 and the generic model GAM, thereby rigorously translating this data into the ABM. Furthermore, the second phase of the methodology ensured a level of comparability with future case studies by prescribing the consistent use of the conceptual framework across cases, even though the generic models may vary. It also introduced a degree of flexibility by allowing for the selection of a generic model suited to the considered case and phenomenon of interest, while keeping the conceptual framework fixed (this chapter). In this way, the second phase of the methodology achieves a balance between comparability and flexibility. Additionally, this chapter demonstrates that the methodology provides the means to develop empirical ABMs. Combined with the methodological steps provided in Chapter 3 for developing theoretical ABMs, this enables the methodology's versatility in supporting both theoretical and empirical ABMs.

In sum, the findings from chapter 4 (for the first phase of the methodology) and this chapter (for the second phase) demonstrate the rigour, ability to balance flexibility and comparability, and versatility of the methodology introduced in Chapter 3, thus answering RQ3.

REFERENCES

[1] V. Nespeca, T. Comes, K. Meesters, and F. Brazier. “Towards Coordinated Self-organization: An actor-centered framework for the design of Disaster Management Information Systems”. In: *IJDRR* 51 (2020), p. 101887. issn: 2212-4209. doi: 10.1016/j.ijdrr.2020.101887.

[2] V. Nespeca, T. Comes, and F. Brazier. “A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry”. In: *JASSS* 26.1 (2023), p. 10. issn: 1460-7425. doi: 10.18564/jasss.5014.

[3] J. M. Epstein. “Agent-based computational models and generative social science”. In: *Complexity* 4.5 (1999), pp. 41–60.

[4] P. Antosz, T. Szczepanska, L. Bouman, J. G. Polhill, and W. Jager. “Sensemaking of causality in agent-based models”. In: *IJSRM* (2022), pp. 1–11.

[5] A. Zagorecki, K. Ko, and L. K. Comfort. “Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments”. In: *JASSS* 13.3 (2009), p. 3. issn: 1460-7425.

[6] C. Adam and B. Gaudou. “Modelling Human Behaviours in Disasters from Interviews: Application to Melbourne Bushfires”. In: *JASSS* 20.3 (2017), p. 12. issn: 1460-7425.

[7] N. Bharosa, J. Lee, and M. Janssen. “Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises”. en. In: *Information Systems Frontiers* 12.1 (Mar. 2010), pp. 49–65. issn: 1387-3326, 1572-9419. doi: 10.1007/s10796-009-9174-z.

[8] L. Palen, K. M. Anderson, G. Mark, J. Martin, D. Sicker, M. Palmer, and D. Grunwald. “A Vision for Technology-mediated Support for Public Participation & Assistance in Mass Emergencies & Disasters”. In: *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference*. ACM-BCS ’10. Swinton, UK, UK: British Computer Society, 2010, 8:1–8:12. isbn: 978-1-4503-0192-3.

[9] M. Turoff, S. R. Hiltz, V. A. Bañuls, and G. Van Den Eede. “Multiple perspectives on planning for emergencies: An introduction to the special issue on planning and foresight for emergency preparedness and management”. In: *Technological Forecasting and Social Change* 80.9 (2013). Planning and Foresight Methodologies in Emergency Preparedness and Management, pp. 1647–1656. issn: 0040-1625. doi: https://doi.org/10.1016/j.techfore.2013.07.014.

[10] J. Whittaker, B. McLennan, and J. Handmer. "A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges". In: *IJDRR* 13 (Sept. 2015), pp. 358–368. issn: 2212-4209. doi: 10.1016/j.ijdrr.2015.07.010.

[11] K. Haynes, D. K. Bird, and J. Whittaker. "Working outside 'the rules': Opportunities and challenges of community participation in risk reduction". en. In: *IJDRR* 44 (Apr. 2020), p. 101396. issn: 2212-4209. doi: 10.1016/j.ijdrr.2019.101396.

[12] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. "Different Modelling Purposes". In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[13] J. Meijering. *Information diffusion in complex emergencies: A model-based evaluation of information sharing strategies*. Apr. 2019.

[14] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. "Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats". In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

[15] J. Watts. *CHIME ABM Hurricane Evacuation Model v1.4.0*. Publisher: CoMSES Computational Model Library. Oct. 11, 2021.

[16] N. Altay and R. Pal. "Information Diffusion among Agents: Implications for Humanitarian Operations". In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[17] J. K. Hazy and B. F. Tivnan. "The impact of boundary spanning on organizational learning: Computational explorations". In: *Emergence* 5.4 (2003), pp. 86–123.

[18] F. M. Brazier, C. M. Jonker, and J. Treur. "Principles of component-based design of intelligent agents". In: *Data & Knowledge Engineering* 41.1 (2002), pp. 1–27.

[19] F. M. Brazier, C. M. Jonker, and J. Treur. "Formalisation of a cooperation model based on joint intentions". In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1996, pp. 141–155.

[20] F. M. Brazier, C. M. Jonker, and J. Treur. "Compositional design and reuse of a generic agent model". In: *Applied Artificial Intelligence* 14.5 (2000), pp. 491–538.

[21] L. K. Comfort, K. Ko, and A. Zagorecki. "Coordination in Rapidly Evolving Disaster Response Systems: The Role of Information". en. In: *American Behavioral Scientist* 48.3 (Nov. 2004), pp. 295–313. issn: 0002-7642. doi: 10.1177/0002764204268987.

[22] S. Abar, G. K. Theodoropoulos, P. Lemarinier, and G. M. P. O'Hare. "Agent Based Modelling and Simulation tools: A review of the state-of-art software". en. In: *Computer Science Review* 24 (May 2017), pp. 13–33. issn: 1574-0137. doi: 10.1016/j.cosrev.2017.03.001.

[23] V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe'er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser, and D. L. DeAngelis. "A standard protocol for describing individual-based and agent-based models". en. In: *Ecological Modelling* 198.1 (Sept. 2006), pp. 115–126. issn: 0304-3800. doi: 10.1016/j.ecolmodel.2006.04.023.

[24] V. Grimm, U. Berger, D. L. DeAngelis, J. G. Polhill, J. Giske, and S. F. Railsback. "The ODD protocol: a review and first update". In: *Ecological modelling* 221.23 (2010), pp. 2760–2768.

[25] V. Grimm, S. F. Railsback, C. E. Vincenot, U. Berger, C. Gallagher, D. L. DeAngelis, B. Edmonds, J. Ge, J. Giske, J. Groeneveld, A. S. A. Johnston, A. Milles, J. Nabe-Nielsen, J. G. Polhill, V. Radchuk, M.-S. Rohwäder, R. A. Stillman, J. C. Thiele, and D. Ayllón. "The ODD Protocol for Describing Agent-Based and Other Simulation Models: A Second Update to Improve Clarity, Replication, and Structural Realism". In: *JASSS* 23.2 (2020), p. 7. issn: 1460-7425.

[26] V. Nespeca, T. Comes, and F. Brazier. "Share: bottom-up disaster information management v1.0.0". en. In: *CoMSES Computational Model Library* (Dec. 2022). doi: 10.25937/3dbz-qv52.

[27] I. Nikolic and A. Ghorbani. "A method for developing agent-based models of socio-technical systems". In: *2011 International Conference on Networking, Sensing and Control*. Apr. 2011, pp. 44–49. doi: 10.1109/ICNSC.2011.5874914.

[28] Y. Barlas. "Formal aspects of model validity and validation in system dynamics". In: *System Dynamics Review: The Journal of the System Dynamics Society* 12.3 (1996), pp. 183–210.

[29] A. Ghorbani, G. Dijkema, and N. Schrauwen. "Structuring Qualitative Data for Agent-Based Modelling". In: *JASSS* 18.1 (2015), p. 2. issn: 1460-7425.

[30] S. Bharwani, M`. Coll Besa, R. Taylor, M. Fischer, T. Devisscher, and C. Kenfack. "Identifying Salient Drivers of Livelihood Decision-Making in the Forest Communities of Cameroon: Adding Value to Social Simulation Models". In: *JASSS* 18.1 (2015), p. 3. issn: 1460-7425.

[31] B. Edmonds. "Using qualitative evidence to inform the specification of agent-based models". In: *JASSS* 18.1 (2015), p. 18.

[32] M. Wooldridge and N. R. Jennings. "Agent theories, architectures, and languages: a survey". In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1994, pp. 1–39.

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[33] M. Wooldridge and N. R. Jennings. “Intelligent agents: Theory and practice”. In: *The knowledge engineering review* 10.2 (1995), pp. 115–152.

[34] P. Antosz, S. Bharwani, M. Borit, and B. Edmonds. “An introduction to the themed section on ‘Using agent-based simulation for integrating qualitative and quantitative evidence’”. In: *IJSRM* 25.4 (2022), pp. 511–515.

[35] S. Achter, M. Borit, E. Chattoe-Brown, and P.-O. Siebers. “RAT-RS: a reporting standard for improving the documentation of data use in agent-based modelling”. In: *International journal of social research methodology* 25.4 (2022), pp. 517–540.

6

Learning to connect in action

Coordinated self-organisation relies on effective information exchange among diverse groups, especially in volatile environments. Informational Boundary Spanners (IBSs) act as key information exchange 'hubs,' but the mechanisms driving their emergence are not well understood. This study aims to fill this gap by developing a method to identify and measure the emergence of IBS and by proposing an Agent-Based Modelling (ABM) framework to understand the mechanisms that drive the emergence of IBS. Among these mechanisms, the ability to learn who provides high-quality information is thought to be critical, but lacks rigorous testing. This learning mechanism is formalized using our ABM framework. The ABM's outputs are analysed using the proposed IBS measurement method. A case study on information sharing in disasters illustrates the method and learning mechanisms. Results indicate that effective IBSs emerge through learning in (a) low-volatility environments with low uncertainty and (b) high-volatility environments with rapid change, provided there are sufficient inter-group connections. By introducing and testing a method to measure and understand the emergence of IBSs from an actor centred-perspective, this chapter answers RQ4. Finally, with the method and ABM framework, this chapter advances coordinated self-organisation and collective intelligence by laying the groundwork for understanding the mechanisms behind IBS emergence and by studying the impact of learning in volatile environments.

6.1. Introduction

Policies and practices for ensuring a sustainable, resilient, and climate-adaptive future rely on collective intelligence across diverse groups [2–5]. Collective intelligence is defined as the shared problem-solving ability that arises from the interaction and combined efforts of a group of individuals, leading to the effective accomplishment of goals even when the environment changes [3, 6, 7]. Fostering collective intelligence strongly relies on the exchange of information among the individuals belonging to the different groups [8–11]. The need for information

Parts of this chapter have been published in the pre-print [1].

sharing is even more prominent in volatile (i.e., rapidly changing and uncertain) environments, where the groups (e.g., governmental organisations, NGOs, and communities) must continually adapt while maintaining coordination of their activities; i.e., coordinated self-organisation is needed. Disaster response exemplifies a situation in which multiple groups operate in a volatile environment and need to exchange information to support coordinated self-organisation [12–14] (Cf. Section 1.1).

Actors within these groups exchange information with each other and with actors in other groups. Some actors do so more successfully than others: over time they become hubs for inter-group information exchange or Informational Boundary Spanners (IBSs) [9, 15–23]. Levina and Vaast [24] find that the formal appointment of this role as IBS, such as through a mandate, does not suffice to ensure effective information exchange. Instead, the role of IBSs in facilitating information sharing among groups emerges through dynamic interactions within and between these groups. More specifically, fostering the emergence of IBSs requires consideration of the interplay between individual group members (micro level), their groups (meso level), and networked interactions among groups (macro level) [20, 25], i.e., it requires an actor-centred perspective (Cf. Section 1.4). This emergent process is contingent on specific conditions at the different levels. For example, it is key that at the micro level an IBS develops an interest in carrying out boundary spanning. Further, the formal nomination of an actor as an IBSs at the group (meso) level can support his/her emergence as such but is not mandatory. And, finally, formal or informal recognition of boundary spanners' authority to negotiate on behalf of their group also plays as key role in the emergence of boundary spanners when considering networked interactions among groups (macro level).

6

While there are some initial empirical insights into the emergence of informational boundary spanning at the micro, meso, and macro levels and mechanisms that drive their emergence, there is thus far no quantitative formalization and analytical modelling framework that studies the emergence of IBSs via computational experiments. This chapter argues that there are three major gaps in the literature: (i) a formalized method to quantitatively analyse how IBSs effectively conveying information across groups emerge; (ii) an analytical modelling framework to analyse and understand the mechanisms behind the emergence of effective IBSs under different conditions of environmental volatility; and (iii) a deeper understanding of the effects of learning on the emergence of IBSs in volatile environments.

Case study research has been invaluable to study boundary spanning [17, 20, 24, 26]. Yet, Agent-Based Modelling (ABM) can complement and enhance case study research by facilitating the systematic analysis and comparison of results from several case studies by capturing interactions from micro to macro levels within a unified modelling framework. This is particularly relevant when investigating emergent mechanisms resulting from complex interactions across multiple levels [27, 28], as seen with IBSs [20]. For instance, by incorporating insights from case studies on individual behaviour at the micro level into an ABM, researchers can simulate a system's macro-level behaviour, assessing whether the simulated emergent patterns replicate and explain empirical observations from other studies

[27]. This approach enables the replication, testing of consistency, and extension of case study research findings and provides directions for further case studies [29, 30].

A fundamental step in enabling a combination of case study research and ABM when studying the emergence of IBSs from an actor-centred perspective is to design a quantitative method for measuring boundary spanning on an individual or micro level. This involves *identifying individuals who emerge as IBSs* by effectively providing the information needed to the groups who need it. Identifying emergent IBSs is vital for examining the interplay between the micro, meso, and macro level conditions that promote such emergence [24]. While several quantitative methods for IBSs have been provided for measuring informational boundary spanning [17, 20, 31–33], these methods typically focus on boundary spanning at the level of one or multiple groups rather than at the level of the individual actor. Specifically, some methods focus on assessing the volume of boundary spanning (e.g., through the frequency of communication) vis a vis operational performance (e.g., time required for project completion) at the group level [19, 31, 32]. Other methods, directly measure the success of IBSs in retrieving information for their group in a timely manner [17, 25, 33]. However, none of these approaches measures how many and which individual agents emerge as effective IBSs. As such, a method to measure the emergence of effective IBSs at micro-level is missing, leading to a lack of understanding in the mechanisms behind the emergence of IBSs.

Such a method provides a basis to build an ABM framework enabling to simulate inter-group information exchange and capture the simulation outputs required to systematically analyse, test, and understand at micro-level mechanisms for the emergence of IBSs under varying circumstances. The characteristics of the external environment, in which the groups operate, are likely to play a crucial role in shaping the emergence of IBSs [34, 35]. The environment consists of factors external to a group's boundary that affect the decisions of individuals within the group and thereby affects the group's ability to achieve its goals [36, 37]. Especially in volatile environments information sharing has been shown to be essential to achieve coordinated self-organisation [14]. Volatility is defined as the level of turbulence and uncertainty that characterize changes in the environment, where turbulence indicates the frequency of change [35], and uncertainty denotes the unpredictability in the occurrence of change [37]. The emergence of boundary spanning (or lack thereof) has been primarily studied for non-volatile environments [17, 24, 26, 38]. Even though volatile situations such as social unrest, crises, or conflicts are increasingly common, little research is available on the conditions that foster the emergence of IBSs in volatile environments. Hazy et al. [35] propose an ABM framework and use it to study the effectiveness of different numbers of IBSs for varying levels of environmental volatility. However, their modelling framework and study assume a predefined number of IBSs and does not account for how and why they emerge. Further, Zagorecki et al. [19] propose an ABM to study the emergence of inter-group information exchange in volatile environments. Yet, their model does not focus on capturing the emergence of IBSs at the micro level. As such, an ABM framework to study the emergence of IBSs at the micro level in volatile environments in missing.

Further, empirical studies have shown that actors in volatile conditions actively *learn* who among their contacts provides high-quality information, subsequently adjusting their information collection preferences to align with these sources [39] (Cf. analysis of system's change in Chapter 5, Section 5.2). Preliminary evidence from Chapter 5 shows that this learning behaviour can lead to the emergence of IBSs the volatile environment of a disaster (Cf. analysis of system's change, Section 5.2). However, the concrete mechanisms between learning and the emergence of IBSs remain poorly understood.

In sum, there are several gaps in the understanding of IBSs. First, a method is needed for measuring the emergence of IBSs at the micro level as key to analyse the underlying mechanisms that drive their emergence. Second, an ABM framework is missing to systematically study mechanisms for the emergence of IBSs at the micro level in volatile environments. Third, a better understanding is required of the effects of learning and the volatility of the situation on the emergence of IBSs.

To address these gaps, this chapter develops a method to measure the emergence of IBSs at the micro-level and introduces an ABM framework enabling to study the emergence of IBSs in volatile conditions through the method. Then, the method and ABM framework are used to analyse and understand learning as a mechanism that potentially results in the emergence of IBSs. To this end, two mechanisms are introduced and compared in the ABM: in the first mechanism, agents exchange information randomly. In the second mechanism, agents continually learn which sources provide the most relevant information and adjust their information collection preferences accordingly. Both mechanisms are studied for different levels of volatility and numbers of connections enabling information exchange among the considered groups during the response to a disaster.

The remainder of this chapter is structured as follows. Section 2 introduces our case study of disaster response in Jakarta as an example of a situation that requires coordinated self-organisation. Section 3 introduces the method proposed for measuring the emergence of IBSs based on existing literature. Section 4 formulates three propositions concerning learning mechanisms for the emergence of IBSs and their impact on inter-group information exchange in volatile environments. Section 5 describes the development of an ABM that captures inter-group information exchange and provides the output required to study the emergence of IBSs through the proposed method. Section 6 illustrates the model parametrization and experimental design aimed at testing the method for capturing the emergence of IBSs and study the propositions through the ABM. Section 7 presents the results of the experiments. Section 8 discusses the implications of these results, leading to considerations regarding the correctness of the method proposed for measuring emergent IBSs, the extent to which the results support the formulated propositions, and what the findings imply for information management, coordinated self-organisation, and collective intelligence in volatile environments. This section also presents directions for future research. Section 8 concludes the chapter.

6.2. Case study: Disaster response in Jakarta

In disaster response, typically multiple and loosely connected organisations (e.g. governmental organisations and NGOs) and groups (e.g. communities) collectively operate in a highly volatile environment. These groups need to exchange information to respond effectively [12–14, 40]. Information exchange in these conditions is particularly challenging as, given the sheer volume and frequency of new information produced during a disaster, the actors are likely to become overloaded with information, which impairs their ability to share and retrieve relevant information [41, 42]. Further, disaster response is typically characterized by high uncertainty, meaning it is often difficult to predict when and from which sources relevant information will become available. As such, disaster response presents an ideal case study to understand the emergence of IBSs in volatile environments.

This research focuses on the case study of Jakarta, Indonesia. Situated on the northwest coast of Java, the world's most populous island, Jakarta is subject to frequent flooding, primarily attributed to its rapid subsidence and ongoing urbanization processes [43, 44]. Jakarta also hosts diverse stakeholders including governmental organisations, NGOs, and community initiatives that need to coordinate, collaborate, and exchange information effectively. Additionally, Jakarta was chosen because, during the data collection period in 2018, numerous international organisations were present in response to the humanitarian response to the Sulawesi Earthquake. The details on the case study including data collection, analysis, and discussion are available in Chapter 4 (Cf. Section 4.4).

6.3. Measuring the emergence of informational boundary spanners

While several functions can be attributed to boundary spanning including information processing, external representation, negotiation, and brokering [17, 34, 45], this chapter focuses on information processing. Information processing or informational boundary-spanning is defined as the activity of searching for information that lies outside the boundary of a group (i.e. that originates in the group's external environment) to find, process, and *share* new and relevant information that can enhance the knowledge of the group [17, 33, 46, 47]. Boundaries are the delimitation of a group or organisation from its environment [48]. Often external information needed by a group is available from other groups. As such, performing the informational boundary spanning function entails fostering the exchange of information among groups.

IBS candidates (actors that can become IBSs), are those who have connections across group boundaries, or 'inter-group ties'. As such, they can potentially search, find, process, and share information across groups, thus performing the informational boundary spanning function.

One approach to measuring the emergence of IBSs may be to simply count the number of IBS candidates that carry out the informational boundary-spanning function. However, while this function may be performed occasionally by many or all potential IBSs, only a few of these actors consistently perform this function and thus contribute significantly to fostering the exchange of new and relevant information across groups [24]. As such, simply counting the number of IBS candidates that perform the informational boundary-spanning function occasionally (e.g. once or a few times) is expected to overestimate the number of IBSs that emerge. Then, measuring the emergence of IBSs requires identifying those actors that not only carry out the informational boundary spanning function but also do so with sufficient consistency to significantly enhance the exchange of new and relevant external information among groups.

6.4. Understanding the emergence of informational boundary spanners

This section presents insights from the literature and the Jakarta case study (Cf. Chapter 4, Section 4.4.4) that were used to formulate propositions and design the ABM for testing the propositions.

6.4.1. Mechanisms for the emergence of informational boundary spanners

Insights regarding potential mechanisms for the emergence of IBSs were gained in the case study of Jakarta. In the words of an information management officer interviewed during the field work in Jakarta (Cf. Chapter 4, Table 4.3):

> "*I was becoming a reference for everyone asking about mailing lists, who is working in a certain area, or what sort of maps are available. So that's the role that I have played*". UN-OCHA Information Management Officer. Collected in October 2018.

This quote shows that an actor can emerge as an IBS not because of direct choice, but through an emergent process resulting from the collective choices and adjustments in the information collection preferences of a multitude of actors. This finding hints at the ability of actors to *learn* the contacts that consistently provide relevant information and adjust their information collection preferences to match such contacts over time. This learning process constitutes a mechanism that occurs at the micro (agent) level, and can lead to the emergence of IBSs at the macro level (Cf. analysis of system's change in Chapter 5, Section 5.2). Such a mechanism is referred to as 'LearNing' or LN in the following. In this study, learning is compared to another mechanism in which actors collect information randomly among their contacts without developing information collection preferences (called 'Random Collection' or RC).

Agents relying on LN develop a preference for collecting from contacts that share relevant information frequently. This significantly increases their chances of finding relevant information. For IBS candidates with inter-group contacts, these preferences tend to favour external contacts, who provide access to external information not readily available within the their own groups. Consequently, IBS candidates relying on LN are more likely to engage with sources outside their group boundaries, accessing new and relevant information more effectively than those using RC, who lack such targeted preferences. Therefore, IBS candidates influenced by LN are more likely to fulfil the informational boundary spanning function (Cf. Section measuring the emergence of IBSs) and emerge as effective IBSs compared to those that rely on RC. This has two consequences. First, a larger portion of IBSs candidates become emergent IBSs, resulting in a higher number of emergent IBSs with LN compared to RC. Second, as a whole, the IBSs that emerge are more effective in finding external information that is relevant and new for their groups with LN compared to RC. The following proposition is formulated.

Proposition 1 (Learning VS Random Collection): When actors learn by adjusting their preferred information sources based on the past quality of information provided by such sources, a higher number of informational boundary spanners emerge that are more effective in retrieving external information than in the case in which actors collect information randomly among their contacts.

6.4.2. The effect of environmental uncertainty

In disaster response, there are typically two types of events in a group's external environment that need to be detected by individuals belonging to the group to inform decision making, namely shocks and announcements (Cf. Chapter 5, Section 5.2). Shocks are unexpected disruptive events such as cascading effects generated by infrastructural failures (e.g., blackouts), riots, or natural disasters. Announcements represent the release of information that is produced and consistently shared by particular groups or agencies such as flood early warnings [49, 50], evacuation orders [27], or needs assessments.

In this study, uncertainty can be associated with the event itself (e.g., concerning the nature and timing of the event) and the source from which information regarding the event is released or made available (i.e. the information origin). Shocks and announcements differ in terms of their uncertainty in the source of information associated with them. In the case of shocks, it is not known when and where a shock will occur, and who will be affected and communicating about it. Consequently, the origin (or source) of information becomes uncertain. As such, shock-related information has an unstable origin. In contrast, announcements are consistently generated from the same source within an information exchange network (e.g., weather forecasting agency in the case of early warnings, or the village leader in the case of evacuation orders). As such, while the time and type of announcement is still uncertain (it is not known when an early warning will be necessary), the source of announcement information is known. Therefore, announcement information is referred to as information with a stable origin.

The combined effect of the stability in information origin and learning on the emergence of IBSs can be conceptualized from the perspective of *information flow paths*. Information flow paths (or simply information flows) represent the contact-to-contact information exchanges through which information spreads within and across groups. These paths originate once information is created from unstructured data, and then routed to one or more of the actors belonging to the groups considered (as shown in Figure 6.1).

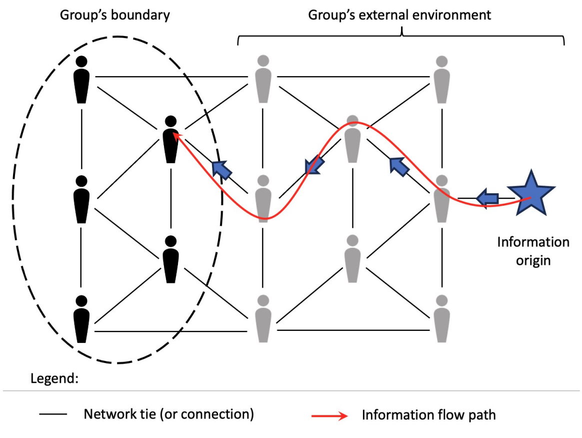

Figure 6.1: Information flow paths illustrating the spread of information from its origin (i.e. node in the network in which new information is introduced) through a series of information sharing activities carried out by the network nodes representing the actors.

The configuration of information flows and whether they reach groups depend on several factors. This study accounts for the following three: (1) information flows depend on the structure of the network through which information can be exchanged within and across the boundaries of different groups (as introduced by [19, 21]). In this case, the network is considered to be constant. (2) information flows are affected by the locations of the network, in which new external information is introduced i.e. the origin of the information. The origin of information can be stable (announcements), or unstable (shocks). (3) The paths depend on the information exchange behaviour and preferences of the actors constituting the nodes in the network.

Whether learning impacts the emergence of IBSs and the ability of groups to retrieve external information is related to the stability of information origin. When the information origin is stable (announcements), the information flow paths originate in the same node. If that information is perceived to be relevant (as assumed for this study), the actors directly connected to the origin will learn and develop a preference towards choosing it as their source. Other actors who are only indirectly connected to the origin (i.e. via other contacts) are likely to develop a preference for the actors among their contacts that are the most directly connected to the origin (i.e. through the lowest number of ties), given they are more likely to consistently receive and share such information earlier than other contacts. Then, at each information exchange along the path, actors are likely to collect from the contacts that are the most directly connected with the information origin. As such, learning is expected to generate shorter information flow paths from the origin of information to the group that needs such information compared to the case in which actors collect information randomly and do not develop preferences.

Conversely, if information has an unstable origin (shocks) the source of information changes, and, thus, agents cannot learn which sources continually provide relevant information. The actors therefore will benefit less from developing information collection preferences. These considerations lead to the following proposition:

Proposition 2 (Stability of information origin and learning): *Learning leads to more effective inter-group information exchange if and only if relevant information is consistently generated by the same actors. If relevant information becomes available from continually changing and uncertain sources (unstable origin) learning has no effect in terms of improving inter-group information exchange.*

6.4.3. The effect of environmental turbulence

Environmental turbulence is the frequency of environmental change [37]. Specifically, turbulence in this study is defined as the frequency of occurrence of events (i.e., shocks, and announcements) representing changes in the environment. In order to detect and adapt to such changes, actors need to find information regarding these events. As such, the higher the level of turbulence the higher the volume of external information that agents need to manage and find. However, actors have a limited capacity to process information [51]. In the case of disasters, the volume and speed of information can be so prominent that actors reach the limit of their cognitive capabilities and become overloaded with information, which impairs their ability to retrieve and exchange the information needed [41, 42]. As such, the authors of this study posit that, for higher levels of turbulence, the performance of the system decreases. Performance is measured as the amount of information concerning environment-altering events that is collected or received by the groups that need such information.

The number of actors that can explore the external environment was shown to play a crucial role in helping groups to detect environmental change [35]. In their study, the actors able to explore the external environment are those with inter-group ties. An increased number of inter-group ties entails a greater number of IBSs candidates who can emerge as IBSs and contribute to detect information concerning events marking environmental change. This is particularly relevant for high levels of turbulence, in which the high volume of information needs to be distributed among a higher number of IBSs to reduce the risk of information overload and enhance system's performance.

Additionally, LN is expected to increase the number of IBSs and improve their performance compared to random collection for high levels of turbulence. Considering that IBSs tend to process and exchange a high volume of information across different groups, they are likely to become overloaded with information. When the available IBSs are no longer able to provide relevant information because of information load, the actors requiring information from them will adapt their information sources through LN to find other actors able to provide the information they need. This may lead the actors to develop preferences towards IBSs candidates that are not yet as overloaded and that thus can support the exchange of information. As such, the adaptability introduced by learning is anticipated to enable actors to collectively distribute the volume of information across a higher number of IBSs, and thus improving overall system's performance compared to the case of RC. This performance increase is dependent on the agents' capacity to select from various IBS candidates resulting from a high number of inter-group ties, leading to the following proposition.

Proposition 3 (Interplay of turbulence, inter-group ties redundancy, and learning): *A higher number of ties among groups results in a higher number of emergent IBSs, enhancing a group's ability to retrieve external information even in highly turbulent environments. This enhanced ability to retrieve external information is particularly pronounced when actors rely on learning to adjust their information collection preferences.*

6.5. Model Design

Agent-based modelling is the modelling paradigm of choice as it enables researchers to explore the collective consequences of individual behaviour [52].

An ABM was developed based on the methodology and ABM proposed in Chapter 3 and 5 and modified to include the learning mechanism found for the Jakarta case study in Chapter 4. The goal of the model is to assess the validity of the method for measuring the emergence of IBSs and to study the mechanisms that influence the emergence of IBSs. A graphical overview of the results of this ABM is shown in Figure 6.2. Further, a conceptual diagram of the entities, states, and tasks included in the model is shown in Figure 6.3. Entities represent essential features of the model with their properties, states, and tasks as presented in the legend of Figure 6.3.

Two main groups of agents are considered in the ABM, namely communities and professional response organisations or simply professionals (including governmental and non-governmental organisations). The system's performance is measured in terms of the percentage of external information needed by each of these two groups that is found by at least one of the actors belonging to the group. Each group has direct access to the information that the other group needs. Therefore, sharing information across group borders is vital. Specifically, communities have direct access to information about shocks, which represent the information needed by professionals. Conversely, professionals can send announcements, which represent the external information needed by communities. The exchange of information among the two groups is enabled through the emergence of IBSs.

Information exchange within and across the two groups takes place via networks of informal and formal ties or contacts (Cf. Figure 6.2). Informal ties are obtained

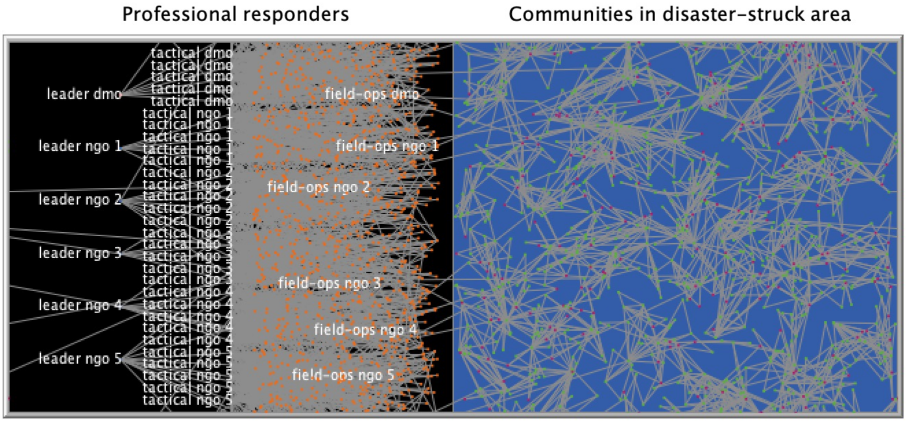

Figure 6.2: Graphical overview of the Agent-Based Model (ABM) developed for this study. The model involves two distinct groups, namely professional responders (on the left, in black) and communities (on the right, in blue) that exchange information. The grey lines represent the formal and informal ties used for information exchange. The ties that cross the border between professional responders and communities are the inter-group ties.

through preferential attachment algorithms based on [53]. Formal ties representing hierarchical structures are introduced within the professional response organisations according to three levels, namely strategic, tactical, and operational. Within such networks, IBS candidates (i.e., those that can potentially emerge as IBSs) are those that have at least one connection with an actor belonging to a group different from their own (Cf. the ties connecting Professional Responders and Communities in Figure 6.2).

The following paragraphs discuss the key features introduced in the model to measure the emergence of IBSs and explore each of the propositions.

Measuring the emergence of IBSs: emergent IBSs are those that consistently provide *new and external information* to a group thus playing a key role in fostering information exchange across the groups (Cf. Section "*Measuring the emergence of informational boundary spanners*"). To apply such a definition, it is crucial to measure each agent’s contribution to information sharing across groups. This measurement is facilitated by the introduction of the ’*number of informational boundary-spanning Function Executions*’ or FEs, where an actor agent increases its FE count each time it provides new and external information to any group that requires it. The number of FEs accumulated by agents are then used to study which of the IBS candidates emerge as IBSs.

Understanding emergence: the first proposition focuses on studying the emergence and effectiveness of IBSs by comparing random information collection (RC) with learning (LN). RC and LN are characterized by different information collection

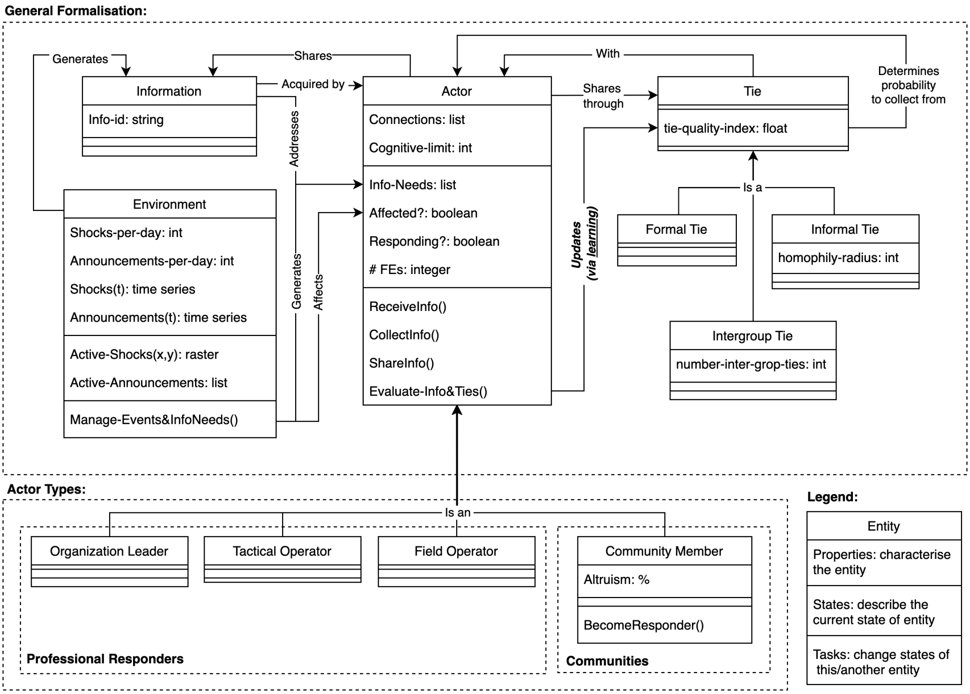

Figure 6.3: Graphical description of entities, their properties, states, and tasks in the developed ABM. The actors and environment are agents in the ABM given they carry out tasks.

preferences. Such preferences are modelled as non-uniform distributions in the probability that agents have to collect from each of their contacts, denoting that some of the agents' contacts are preferred compared to others. For RC, the information collection probabilities assigned by an agent to its contacts are equally divided among all contacts, indicating that the agent has no preferences (uniform distribution). For LN, each agent develops and adjusts its information collection preferences over time (possibly leading to a non-uniform distribution). Specifically, a reinforcement learning algorithm is used to adjust preferences over time for each agent based on the relevance of the information provided by each of the agent's contacts from the beginning of the simulation up to the current time step. The adopted reinforcement learning algorithm is Q-learning (see Appendix C).

The second proposition considers the interplay of learning and uncertainty. To test the impact of stability in information origin, announcements (with a stable information origin) and shocks (with an unstable information origin) are introduced in the model. The degree of uncertainty is determined by the parameters *shocks per day* and *announcements per day*. For instance, if *shocks per day* is set to 0 and *announcements per day* is set to a value greater than 0, environmental uncertainty is considered to be low, as only stable-origin announcements are considered.

The third proposition focuses on studying the combined effect of learning, turbulence, and number of inter-group ties on the emergence and performance of IBSs. Varying levels of turbulence are captured by the different frequencies in the number of shocks and announcements (parameters *shocks per day* and *announcements per day*) considered. The number of ties across communities and professional responders are specified by the parameter *number of inter-group ties*. The inter-group ties are introduced in the model with a preferential attachment algorithm modified to choose pairs of agents belonging to different groups with a likelihood that depends on their current degree (i.e. number of ties). Bounded rationality is captured by limiting the amount of information that actors can process, share, and collect to 3 pieces of information within each simulation step (set the 'info. processing limit' parameter in the model).

Regarding the temporal and spatial scales considered in this model, the time step of simulation is 10 minutes, while the duration of the simulation is 4 days. Spatial scale is considered at an abstract level in this model as the actors exchange information through networks. As such, a specific spatial scale is not assigned in this case.

6.6. Methods

This section describes the way the model parameters were set and the experiments that were run to test the propositions.

Model Parametrization

Three parameters were constant for all experiments namely: duration of a simulation, the learning rate, and the information processing limit. The duration of each simulation was set to 4 days to simulate information exchange in the early stages of disaster response, a phase in which volatility is especially pronounced and rapid inter-group information exchange and coordination are particularly crucial [54, 55]. The learning rate was set to a relatively low value (assumed to be 0.1) as the time step in the simulation is small (10 minutes) compared to the chosen duration of the simulation, requiring a smaller learning rate to compensate for the high frequency with which information exchange preferences are updated (up to every 10 minutes). Finally, the information processing limit was set to a value of 3, representing humans' limited ability to process information per unit of time (in this case every 10 minutes) [51].

Experimental design

In total, four batches of experiments were designed to study (a) the method for measuring the emergence of IBSs and (b) each of the 3 propositions as shown in Table 6.1. Experiment 0 focuses on testing the approach for capturing and measuring the emergence of IBSs. The simulations are run for varying numbers of inter-group ties. Experiment 1 focuses on simulating the impact of the two different information collection mechanisms to study Proposition 1. Next, Experiment 2 studies Proposition 2 and thus investigates the interplay between learning and varying levels of uncertainty (stability in information origin) by combining different levels of *shocks per day* and *announcements per day*. Finally, Experiment 3 explores Proposition 3 and thus focuses on the interplay between varying levels of environmental turbulence (established with the parameters *shocks per day* and *announcements per day*), learning (LN VS RC), and the number of inter-group ties (established with the homonym parameter). These experiments are run through the service provided by the Delft High Performance Computing centre [56].

Parameters	Experiment 0 (method): Measuring emergent IBSs	Experiment 1 (Proposition 1): Comparing LN and RC	Experiment 2 (Proposition 2): Effect of Environ. Uncertainty	Experiment 3 (Proposition 3): Effect of Environ. Turbulence
Info. Collection Mechanism	RC	LN, RC	LN, RC	LN, RC
shocks per day	10	10	0, 10, 20	1*, 5*, 10*, 15*, 20*
announcements per day	10	10	0, 10, 20	1*, 5*, 10*, 15*, 20*
number of inter-group ties	1, 2, 5, 10, 20, 30	20	20	1, 2, 5, 10, 20, 30
duration of the simulation (days)	4	4	4	4
learning rate	N.A.	0.1	0.1	0.1
info. processing limit	3	3	3	3
number of repetitions	80	40	40	20
total simulations	480	80	720	1200

Table 6.1: Parameters setting for the simulation experiments aimed at testing each of the propositions. The experiments were full factorial with the exception of the values marked with an asterisk '*'. The use of * for experiment 3 indicates that for each simulation in the experiment an equal value of shocks per day and announcements per day is considered (e.g. 10 shocks per day and 10 announcements per day) rather then their full factorial combination. LN = LearNing, RC = Random Collection.

6.7. Results

This section illustrates the results of the experiments shown in Table 6.1.

6.7.1. Experiment 0: Measuring the emergence of informational boundary spanners

Figure 6.4 illustrates the distribution of the number of instances where agents with inter-group ties (IBS candidates) effectively contribute new and relevant external information to the groups that need it, earning them informational boundary spanning Function Executions (FEs).

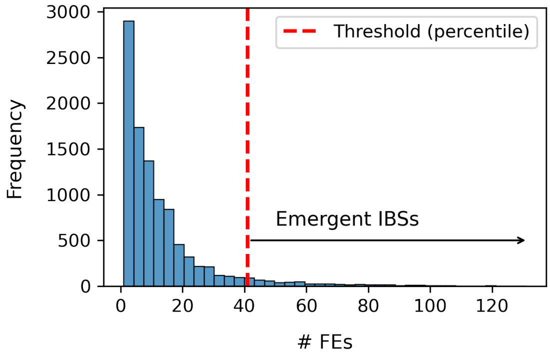

Figure 6.4: Frequency of occurrence of # FEs (number of informational boundary-spanning Function Executions) obtained by the IBS candidates, and the threshold used to capture the emergent IBSs.

The distribution reveals that several IBS candidates attain relatively few FEs, while only a few candidates achieve a high number of FEs. This finding illustrates that a few IBS candidates contribute to a great extent to inter-group information exchange by providing new and relevant information to the groups who need it, while many other candidates do not contribute significantly. The candidates that contribute significantly to inter-group information exchange qualify as emergent IBSs. One approach to identify these candidates is to assume that those that achieve a number of FEs above a given threshold contribute effectively also at the inter-group level and thus qualify as emergent IBSs (Cf. the red vertical line in Figure 6.4). Such threshold or thresholds should be high enough to avoid capturing those IBS candidates that obtain only a few FEs (and as such do not considerably improve inter-group information exchange), but also not too high to avoid not capturing agents that may not have the highest FEs but still contribute significantly to inter-group information exchange. However, it is unclear how to select a threshold that satisfies these conditions.

To investigate the effects of the choice of this threshold, Experiment 0 focuses on studying the implications of adopting different thresholds, namely the 1st, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th percentiles in the frequency distribution shown in Figure 6.4. For each of these thresholds, the number of IBSs emerged is plotted against their effectiveness at the inter-group level, measured as the % of external information needed found by the groups. Figure 6.5 illustrates the results for selected thresholds (i.e. the 1st, 30th, 60th, 90th percentiles) to enhance clarity of representation. These results show that for all considered thresholds a higher number of emergent IBSs corresponds to a higher performance. Further, the number of emergent IBSs grows considerably when increasing the threshold. This figure, however, does not consider the number of IBS candidates available, which represents the maximum number of IBS that can emerge. As such, a more in depth analysis is required that considers not only the threshold adopted, but also the number of IBS candidates available.

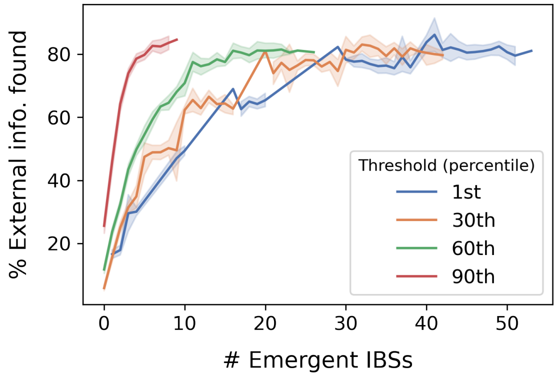

Figure 6.5: Relationship between the number of IBSs that emerged and the % of external information found by the groups who need it for different values of the threshold set as a percentile in the distribution of FEs from Figure 6.4.

6

To analyse emerging IBSs across varying numbers of IBS candidates and threshold settings, it is key to consider that the number of IBSs candidates depends on the number of Inter-Group Ties (# IGTs) available among groups. Precisely, the number of IBS candidates is twice # IGTs given that each connection ties two agents who can both emerge as IBSs. As such, the analysis depicted in Figure 6.5 is expanded to consider not only different thresholds (in this case all of those between the 1st and 90th percentiles), but also different # IGTs. Figures 6.6.A to 6.6.J depict the results. A comparison of these figures reveals that, at low thresholds, as depicted in Figures 6.6.A to C, nearly all IBS candidates transition into emergent IBSs. For instance, with 10 inter-group ties (meaning 20 IBS candidates), the emerging number of IBSs tend to be around 20, underscoring the high conversion rate of IBS candidates into actual IBSs (Cf. Figure 6.6.A, B, and C). Furthermore, the simulation results cluster in specific areas of the plot when holding the number of inter-group ties constant. This clustering suggests minimal variability in both the number of emerging IBSs and the overall system performance. Such lacking variability shows the little sensitivity in capturing emergent IBSs provided by low thresholds. Conversely, for high thresholds such as the 90th percentile (Figure 6.6.D), there is significant variability in the number of emergent IBSs, yet the percentage of external information remains relatively constant, as shown by the horizontal lines. This shows that the emergent IBSs captured with high thresholds do not contribute significantly to effective inter-group information exchange. Thresholds between these extremes, like those between the 30th and 80th percentiles (Figures 6.6.D to 6.6.I), show variability in the number of IBSs

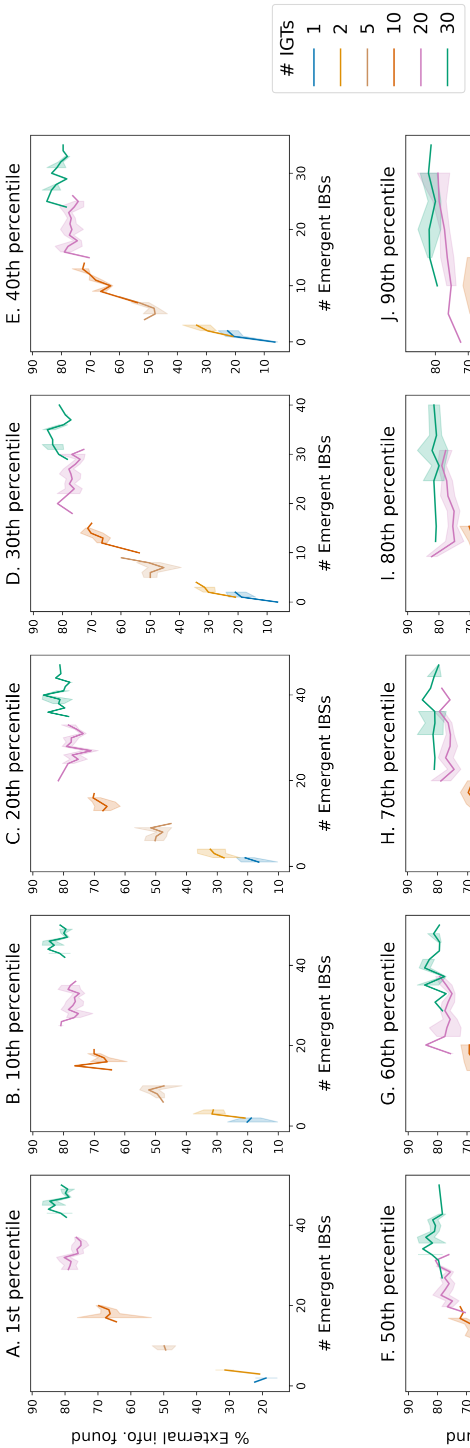

Figure 6.6: Number of IBSs that emerged for each of the thresholds considered and for different numbers of Inter-group Ties (# IGTs).

emerged. Further, for an increase in the #IBSs, the % of external information found also increases, showing how the additional emergent IBSs captured positively contribute to fostering inter-group information exchange. One exception to such an increase is observed for the 80th percentile and 20 IGTs when the number of emergent IBSs found is 3. This is most likely an outlier given that the plot does not show a confidence interval around the value.

These findings illustrate that the method proposed in this chapter captures the number of emergent IBSs that significantly contribute to providing new and external information to groups, thereby supporting effective inter-group information exchange.

However, for this method to be effective, thresholds need to be carefully chosen according to two criteria. First, adequate thresholds are not too low, thus presenting sensitivity to the emergence of varying numbers of IBSs across different simulations. Second, such thresholds are not too high, meaning that when the number of IBSs captured through the threshold increases, also their effectiveness in fostering inter-group information exchange increases.

These two criteria are sufficient to find multiple adequate thresholds rather than a single one (in this case those between the 30th and 80th percentiles), leaving an open question as to whether adopting different adequate thresholds will provide different results when studying the emergence of IBSs. As such, rather than simply choosing one of the adequate thresholds, it is key to use multiple thresholds and assess the consistency of the findings obtained. The remaining experiments (1 to 3) are analysed with six thresholds, namely the 30th, 40th, 50th, 60th, 70th, and 80th percentiles. For brevity, the following sections show the results for the 60th percentile. However, a comparison of the IBSs emergence results obtained with the six percentiles chosen are presented in Appendix D.

6.7.2. Experiment 1: Learning VS Random Collection

Proposition 1 is composed of two parts. The first part indicates that when actors learn and adjust the information collection preferences based on the quality of information provided by their contacts (LeaRning mechanism or LN) this leads to the emergence of more IBSs compared to the case in which actors collect information randomly (Random Collection mechanism or RC). The second element of the proposition states that when actors learn (LN), this leads to the emergence of IBSs that are more effective in fostering inter-group information exchange compared to random collection (RC). In the following these two parts are assessed against the results of experiment 1.

Figure 6.7 shows the results of experiment 1 including the emergence of IBSs (left) and their performance (right) respectively for the information collection mechanisms LN and RC.

First, Figure 6.7 (left) illustrates how, compared to RC, LN results in an average increase of about two emergent IBSs. The 5th, 25th, 75th, and 95th percentiles and the median are also shifted towards higher values in the case of LN compared to RC. The interquartile range of the number of IBSs emerged is larger for LN than in the case of RC, showing that learning also increases the variability of the results.

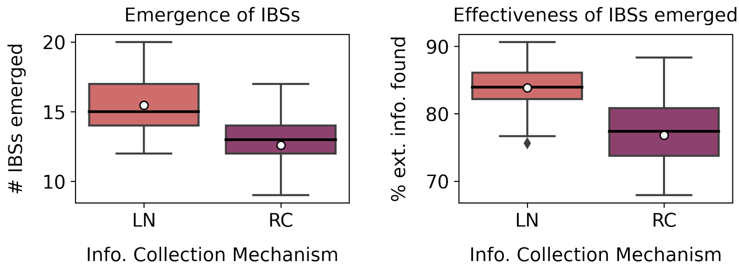

Figure 6.7: Results of Experiment 1: Effect of the information collection mechanisms Random Collection (RC) and LearNing (LN) on the # IBSs emerged (left) and the % of external information found by the groups that need it (right). The white dots represent the averages.

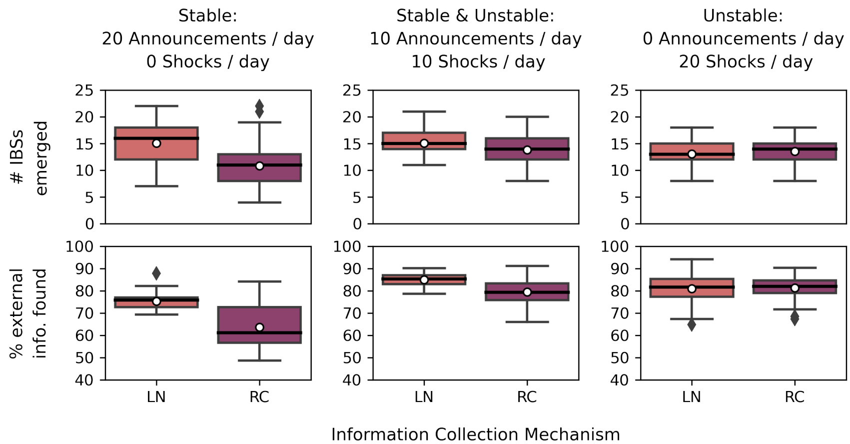

Figure 6.8: Results of Experiment 2: Interplay between the information collection mechanisms Random Collection (RC) and LearNing (LN), and varying environmental uncertainty. The effect of such an interplay is assessed for (a) the emergence of Informational Boundary Spanners (IBSs) (upper row) and on (b) the effectiveness of such IBSs in enabling groups to retrieve external and relevant information (lower row). The varying environmental uncertainty is characterized by stable (20 announcements per day - left column), mixed stable and unstable (10 announcements per day and 10 shocks per day - middle column), and unstable (20 shocks per day - right column) origins of external information.The white dots represent the averages.

However, the 5th percentile is closer to the median in the case of LN compared to RC, illustrating how, despite its higher variability, the distribution is skewed towards higher values of # IBSs emerging in the case of LN compared to RC. These results supports the first part of Proposition 1 by showing that the number of IBSs emerged tends to increase with LN compared to RC.

Second, according to Figure 6.7 (right) the effectiveness of IBSs measured as the percentage of external information retrieved by each group increases roughly by 7.5% on average with LN compared to RC. The 5th, 25th, 75th, and 95th percentiles, and the median shift towards higher values in the case of LN compared to RC. Additionally, the interquartile range for LN is considerably reduced compared to RC, illustrating how, in combination with the higher median, the retrieval of external information is more likely to be higher in the case of LN compared to the case of RC. These results support the second part of proposition 1 by showing that when agents learn (LN) the IBSs that emerge are able to find and provide higher percentages of the external information needed by groups compared to the case in which information is collected randomly (RC). In sum, both parts of Proposition 1 are supported by the results.

6.7.3. Experiment 2: The effect of environmental uncertainty (stability of information origin)

Figure 6.8 shows the results of Experiment 2 regarding the emergence of IBSs (upper row) and their performance (lower row) for both LN and RC. These results include different combinations of frequencies in shocks and announcements, namely 20 announcements per day (left column), 10 shocks per day and 10 announcements per day (middle column), and 20 shocks per day (right column). In all three cases the number of events (shock, announcements, or combinations of them) amount to a total of 20 for each day of simulation to ensure comparability among them.

The results show that, in the case of announcements (Cf. left column of Figure 6.8), LN increases the # IBSs emerged (by roughly 7 IBSs) and their performance (by around 15%) compared to RC.

When announcements and shocks are combined, as illustrated in the middle column of Figure 6.8, LN leads to an average emergence of 2 additional IBSs and a performance increase of 7% over RC. However, these gains are modest when compared to scenarios solely involving announcements. For announcements only (see left column of Figure 6.8), there was a notable rise of 7 emergent IBSs and a 15% performance improvement.

Next, in the case of shocks (Cf. right column of Figure 6.8), the number of IBSs that emerge and their performance does not change significantly with LN or RC.

These findings support Proposition 2 by showing that the effect of learning depends on stability of the information origin. If the information origin is stable (announcements), then learning leads to an increase in the number of IBSs and in their effectiveness in improving inter-group information exchange. Conversely, if the source of information is unstable (shocks), learning has little effect.

6.7.4. Experiment 3: The effect of environmental turbulence

This experiment focused on the emergence of IBSs and their effectiveness under different levels of turbulence and numbers of Inter-group Ties (# IGTs). The level of turbulence consists of the frequency of disruptive events (shocks and announcements) occurring every day of simulation and generating external information needs for the groups (measured as external information needed per day). In other words, the turbulence level is set as the sum of shocks per day and announcements per day. An equal number of shocks and announcements per day is considered in all experiments. As such, a Turbulence level of ten corresponds to five announcements per day plus five shocks per day. The results are shown in Figure 6.9.

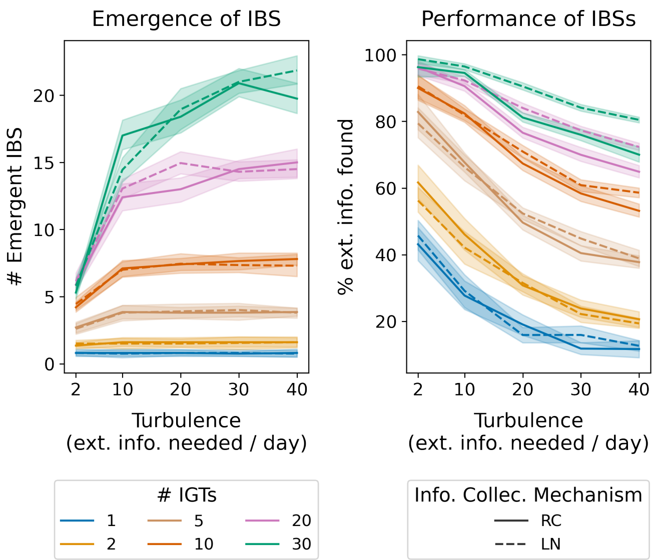

Figure 6.9: Results of experiment 3: Effect of increasing environmental turbulence on the number of Informational Boundary Spanners (IBSs) emerged (left) and their collective performance in exchanging external relevant information across groups (right) for different numbers of Inter-group Ties (# IGTs) between communities and professionals, and for the two information collection mechanisms LN (LearNing) and RC (Random Collection).

Figure 6.9 on the left shows that for higher turbulence a higher number of IBSs emerges. The number of IBSs that emerge grows with the # IGTs, and it does not change significantly with the information collection mechanism considered (LN or RC).

Figure 6.9 on the right shows that for higher levels of turbulence (and corresponding increasing information needs), the share of the external information that is retrieved decreases. However, a higher number of inter-group ties increases the performance of the system at all levels of turbulence. Further, such performance increases with LN compared to RC for high levels of environmental turbulence (10 or more events per day) if the number of inter-group ties is also high (20 or more IGTs).

In sum, these findings support proposition 3 for two reasons. First, independently from the information collection mechanism, more inter-group ties are associated with the emergence of more IBSs that more effectively convey information across groups. Second, for high numbers of IGTs and levels of environmental turbulence, the performance of the IBSs emerged increases with LN compared to RC.

6.8. Discussion

This section discusses the implications of the findings, and suggests directions for future research.

6.8.1. Measuring emergent IBSs

This study introduced a method for measuring the emergence of IBSs. Compared to previous work that measures the emergence of informational boundary spanning at the level of a group or groups [17, 19, 20, 31–33], the method introduced here directly measures the individual agents that emerge as IBSs. Emergence of IBSs can thus be tracked in greater detail, and the heterogeneous characteristics of those that emerge as IBSs can be observed at the micro level. Further, the interplay between the individual, group, and inter-group levels and its impact on the emergence of effective IBSs can be studied through this method. These aspects are crucial to inform the design of effective information management strategies that foster the emergence of IBSs, enhance inter-group information exchange, and support coordinated self-organisation and collective intelligence [24].

To qualify as IBSs, the IBSs candidates need to fulfil a minimum "number of informational boundary spanning Function Executions" or FEs (i.e. a minimum threshold) that enables them to significantly improve information exchange among groups. To ensure the correctness of this method, thresholds must be carefully selected based on two criteria: they should not be too low to maintain sensitivity to varying occurrences of IBSs in different simulations, and not too high to ensure that as more IBSs are detected, their collective ability to enhance inter-group information exchange also increases. Here, inter-group information exchange is measured as the percentage of the total external information needed found by the groups.

Experiment 0 showed that this method enables to measure emergent IBSs by individuating those actors that effectively contribute to inter-group information exchange. Further, multiple adequate thresholds were found to satisfy the two criteria mentioned above. To clarify whether adopting different adequate thresholds lead to different results when studying the emergence of IBSs, the results of

Experiments 1 to 3 were analysed and compared with six adequate thresholds: the 30th, 40th, 50th, 60th, 70th, and 80th percentiles of the FE distribution for IBS candidates. The results of this comparison in Appendix D show that adopting different adequate thresholds does not change the conclusions of the experiments as Propositions 1 to 3 remain supported by the findings independently of the thresholds considered. However, Appendix D also shows that it is still essential to consider a wide range of adequate thresholds when studying the emergence of IBSs. Specifically, a discrepancy was found in Experiment 2 in the results observed with the minimum and maximum thresholds (respectively, the 30th and 80th percentiles). These results were considered as outliers and thus discarded given their extreme value, inconsistency in the effects found, and the fact that the majority of the other thresholds indicated consistent results (Cf. Appendix D). This process illustrates the importance of considering multiple thresholds and carefully analysing any discrepancies that may arise. Such an analysis allows one to determine whether discrepancies indicate inconsistencies in the findings that require reconsideration or modification of the conclusions, or if they simply represent outliers resulting from the adoption of extreme thresholds (i.e., too low or too high).

In sum, this method enables the study of the emergence of IBSs at the micro (or individual) level. To ensure the method's correctness, it is first crucial to select thresholds that are neither too low nor too high, thereby effectively capturing emergent IBSs that contribute to inter-group information exchange. Second, a wide range of adequate thresholds should be considered to test consistency across results on the emergence of IBSs and to assess whether any discrepancies are outliers or if the conclusions need to be reconsidered and modified in light of such discrepancies.

6.8.2. Understanding emergent IBSs

First, this chapter introduces a novel agent-based modelling (ABM) framework that enables to study the emergence of IBSs in volatile environments. This ABM simulates inter-group information exchange and outputs the number of times IBS candidates fulfil the informational boundary spanning function at the micro level, as well as their overall effectiveness. This provides the basis to identify those that emerge as IBSs through the proposed method and to systematically test mechanisms for their emergence in volatile conditions. Compared to previous ABM frameworks introduced to study inter-group information exchange and boundary spanning in volatile conditions [19, 35], this framework measures the emergence of IBSs rather than imposing a predefined number of IBSs a priori [35], and captures this emergence at the micro or individual level rather than solely at the macro level [19].

Second, this study furthers the understanding of learning for the emergence of IBSs. Learning entails that each agent develops information collection preferences over time based on the past quality of information provided by the agent's contacts. This mechanism was compared to the case in which actors collect information randomly. As posited in Proposition 1 and supported by the results of Experiment 1, learning leads to the emergence of more IBSs as compared to random information collection, and these IBSs contribute to more effective inter-group information exchange. Learning therefore is a micro-macro mechanism as learning at the micro level leads to the emergence of IBSs and effective inter-group information exchange at the macro level. This finding confirms the results of the study by Levina and Vaast [24] and extends it to volatile environments by showing that effective boundary spanners emerge through a process resulting from the decentralized interactions among actors belonging to different groups. It also adds to the work by Marrone et al. [20] by showing *how* micro level antecedents such as learning and the availability of connections with other groups can lead to macro level outcomes through an emergent process.

Third, this study highlights the necessity to consider environmental volatility, i.e. the uncertainty and turbulence of the environment, for studying the emergence of IBSs. As posited in Proposition 2 and corroborated by the findings from Experiment 2, the effect of learning on the emergence and efficiency of IBSs is contingent on environmental uncertainty and specifically on the stability of the information source or origin. If the information origin is stable, as in the case of announcements, the number of IBSs and their performance in enhancing inter-group information exchange increases when the agents adopt learning. In contrast, an unstable information source, as in the case of shocks, renders learning ineffective. This difference can be explained by the differences of information origin and network structures: while announcements are constantly originating from the same location of the network, shocks originate from random locations in the disaster-affected area of the model. Under learning, announcements propagate through the network following increasingly strong preferential channels. In contrast, the way shocks propagate continually changes depending on where the shock occurred and which nodes/actors in the network find this information and share it with others. These results explain why learning has little effect on shocks or more generally information of unstable origin: when information can come from ever-changing locations of the network, developing information collection preferences for the contacts that provided the most relevant information in the past has the same effect as collecting information randomly given that none of the agents tends to consistently provide relevant information due to the instability of the information origin.

Proposition 3 is supported by the findings of Experiment 3 and suggests that an increased presence of inter-group ties leads to the emergence of a higher number of IBSs that, as a collective, can more effectively facilitate the exchange of information between groups. This effect occurs even for high turbulence and when considering the actors' limited information processing and sharing capability. Further, for high levels of inter-group ties and environmental turbulence, learning leads to higher performance than in the case of random information collection. Such an improvement is negligible for low numbers of ties and becomes evident for 20 and 30 inter-group ties. This pattern can be attributed to the agents' collective capacity to discern through learning the most effective IBS candidates for relaying external information (e.g., those that are exposed to less information load) as they change over time. Further, the fact that learning has an effect only for 20 or more inter-group connections illustrates that a sufficiently extensive network of inter-group ties is crucial for enabling agents to choose from various IBS candidates through learning.

In summary, this chapter demonstrates how the proposed method enables the measurement (Cf. Section 6.8.1) and understanding of IBS emergence from an actor-centred perspective 6.8.2), thereby answering RQ4. First, the method facilitates the measurement of IBS emergence at the micro level (see previous section). Second, when combined with the developed ABM, the method supports the study and understanding of an actor-centred mechanism for IBS emergence. This mechanism is actor-centred as it considers the interaction among factors at the micro level (i.e., learning and bounded rationality as the limited capacity to process information over time), meso level (i.e., inter-group connections), and macro level (i.e., groups involved in disaster response operations and environmental volatility).

6.8.3. Implications for Collective Intelligence and Coordinated Self-organisation

This study contributes to the collective intelligence literature by illustrating *how* a cognitive process at the individual level (i.e., learning [57]) can support the collective selection of actors (the IBSs) that effectively convey information across multiple groups to support their coordinated self-organisation [58, 59]. This can be considered to be collective intelligent behaviour given that the groups are able to select actors that are more effective than others at carrying out particular tasks or activities - in this case fostering inter-group information exchange - thus possibly improving the system's performance (groups' retrieval of the external information needed for decision making and coordination) [60]. While Chapters 1 and 2 discussed how coordinated self-organisation is required for collective intelligence in volatile environments (Cf. Sections 1.1 and 2.1.3, respectively), this chapter shows that some forms of collective intelligence, i.e., collective learning and selection of effective IBSs that foster inter-group information exchange, can support coordinated self-organisation.

Further, this study illustrates that this collective intelligent behaviour is contingent upon the characteristics of the environments in which groups operate [36, 61] and specifically its volatility (characterized by uncertainty and turbulence). When environmental uncertainty is very high and, as such, information presents unstable information origins, learning does not lead to a collectively intelligent behaviour. This effect is reversed when at least some of the information has as stable origin. Additionally, when the turbulence of the environment is very high, learning produces a collectively intelligent behaviour only for high levels of inter-group connectivity.

6.8.4. Implications for Information Management

Understanding the learning mechanism and its interplay with environmental uncertainty, environmental turbulence, and the number of inter-group ties available can provide useful insights for the design of information management strategies that foster inter-group information exchange, coordinated self-organisation, and collective intelligence in volatile environments. Two main indications for policy can be drawn from this study respectively related environmental uncertainty and turbulence.

Concerning environmental uncertainty and the associated stability of information origin, this research shows that learning increases the number of IBSs that emerge and the external information they retrieve only in the case of stable origin. However, in this chaotic and unpredictable world marked by increasing volatility, the environments in which groups operate are often characterized by high levels of environmental uncertainty and thus information with an unstable origin (shocks). As such, effective strategies for managing this type of information are required to support effective information exchange across groups that fosters coordinated self-organisation and collective intelligence in volatile environments. If information with an unstable origin can be re-directed to stable origins which consistently provide it to other actors, this will enable the actors develop an information collection preference for this source through learning and more effectively retrieve the external information needed. Such a change in stability could be achieved by gathering shocks through crowdsourcing and sharing them widely through a fixed node in the information exchange network such as an online platform, website, or social media account (thus establishing a stable information origin) [62].

With regards to environmental turbulence, a higher number of inter-group ties was consistently found to be a key element in fostering the emergence of IBSs, especially at high levels of environmental turbulence and at any level of environmental uncertainty. To enable the availability of such inter-group ties it is key to build trusted relationships across groups that can be leveraged when external information needs to be retrieved by the group from its environment, also known as bridging social capital [63]. This aligns with previous research indicating that bridging social capital supports inter-group information exchange and resilience in volatile settings such as disaster response [64–66] and supply chain operations [67–69]. Additionally, this study shows the importance of the degree of bridging social capital (measured by the number of trusted inter-group ties available) in facilitating effective information exchange via emergent IBSs, even amidst high volatility and uncertainty. Thus, policy interventions should prioritize establishing bridging social capital through initiatives that build trusted connections among different groups, such as between communities and professional responders [2, 70].

6.8.5. Future research

This study focused on theory building by advancing propositions concerning the emergence of IBSs that effectively convey information across groups in volatile environments. These propositions are designed based on the literature, empirically grounded in the case study of disaster response in Jakarta, and systematically explored through an empirical ABM. Despite this grounding, the propositions still result from exploratory research on one case study. As such, generalizing the propositions will require further investigation and testing e.g. via additional case studies and experiments. Future studies should extend beyond disasters (as in this research), to include other volatile environments such as supply chains during rapid market shifts.

Moreover, this study focused on the emergence of boundary spanners, and was agnostic to the specific information technology that was used. At the same time, evidence suggests that information technology can play a key role in information sharing and the emergence of inter-group information exchange in volatile environments [71] and also interplay with the emergence of IBSs [24, 72]. Such an interplay, is still poorly understood in volatile environments and requires further research.

Additionally, agents in this study exhibit non-strategic behaviour in information exchange, lacking consideration for long-term goals or personal agendas (i.e., they are myopic, Cf. Appendix C). However, previous research indicates that strategic information exchange occurs, for example, to persuade others to reciprocate with valuable information, to obfuscate or withhold information, or to spread misinformation to advance personal or organisational interests [14, 73]. This strategic sharing can alter recipients' information collection preferences and impact the flow of information, thereby influencing the emergence of IBSs. Future research should investigate how strategic sharing, combined with learning and adaptation in information exchange preferences, affects the emergence of effective IBSs.

Next, this study assumes a constant information exchange network, however, establishing new connections to retrieve relevant information external to a group is often considered as one of the tasks carried out by boundary spanners [17, 25, 74]. As such, the network can also change and develop over time. This is for example the case in the context of international humanitarian response operations in which, due to the high staff turnover, few connections across groups enabling inter-group information exchange are available and new ones need to be established ad-hoc during the humanitarian response [22]. Zagorecki et al. [19] studies the emergence of inter-group information exchange when enabling actors to establish connections that decay over time when unused. Their study finds that these networking activities lead to the emergence of actors that convey information across groups. However, the focus of their research is placed on the quantity of information rather than on its quality (e.g., relevance of the information exchanged), and it does not measure the emergence of effective IBSs at the micro level. As such, further research is required to study the impact of networking activities and contact decay on the emergence of effective IBSs in volatile environments from the micro level perspective.

Further, this study does not investigate the characteristics that make certain IBS candidates more likely to emerge. However, it is plausible that specific traits—such as network centrality—may influence IBS emergence. Highly central agents are typically exposed to large volumes of information, increasing their chances of identifying and disseminating relevant content across groups. This may enhance their ability to perform the boundary-spanning function repeatedly, making them more likely to emerge as IBSs. Conversely, in highly volatile environments, high centrality could lead to information overload, potentially reducing an agent's effectiveness and the likelihood of their emergence as an IBS. Therefore, agents with a moderate level of centrality—sufficient to access information efficiently but not so high as to become overwhelmed—may be most likely to emerge as effective IBSs. Additionally, centrality may play a less significant role when agents are capable of learning, as learning enables adaptation to local conditions and reduces reliance on network structure compared to random information sharing. As such, future research should examine the role of centrality and its interaction with learning in fostering the emergence of IBSs under varying levels of environmental volatility. Another trait that may influence the emergence of certain IBS candidates over others is their formal nomination by the organization to which they belong to assume this role. As demonstrated by [24], formal nomination—although not sufficient on its own—can facilitate the emergence of IBSs. However, their study focuses on non-volatile environments. Consequently, further research is needed to investigate the conditions under which formal nomination supports the emergence of IBSs in volatile environments.

In addition, while learning was identified as a potential IBSs emergence mechanism empirically (via the Jakarta case study), the choice of Q-learning and of its parameters were educated guesses. Yet, different machine learning algorithms and parameter settings are likely to capture varying learning dynamics (e.g., faster or slower adaptation, greater or lesser responsiveness to changing conditions), possibly leading to different results. Future research will focus on conducting controlled behavioural experiments to observe how individuals learn which contacts provide relevant information. By tracking patterns of information sharing in volatile environments, researchers will collect data across repeated trials. This data will be used to benchmark various machine learning models (including Q-learning) in their ability to capture human learning, enabling their comparison, calibration, and validation. The best-performing models will then be implemented—either individually or as part of a model committee—within the ABM to enhance its realism in simulating individual human learning processes.

Finally, the adaptation of information exchange preferences over time can not only lead to the emergence of IBSs that facilitate information exchange across groups but also to the formation of information exchange bubbles that isolate groups from others leading to fragmentation and a lack of coordinated self- organisation [14]. In other cases, fragmentation in the form of pre-defined functional division of routine tasks (or differentiation) among different organisations and groups (e.g., police and fire fighters) can be beneficial for operational efficiency and coordinated self-organisation as it enables to operate according to pre-established standards and procedures that require less integration and information exchange [36]. Such fragmentation can, however, be lost in volatile contexts as actors and their groups adapt their activities to a continually and unpredictably changing environment [75]. In such situations, inter-group information exchange via IBSs is necessary to reinstate this fragmentation and support coordinated self-organisation [75]. Further research is required to study the interplay between the emergence of IBSs on one hand and the formation of information bubbles, fragmentation, and coordinated self-organisation on the other.

6.9. Conclusions

In this increasingly chaotic and rapidly-changing world different groups including governmental and non-governmental organisations, and communities need to work together effectively while operating in volatile conditions (characterized by high turbulence and uncertainty). To this end, the prompt exchange of vital information concerning environmental change across groups is crucial to support coordinated self-organisation and collective intelligence. This chapter aimed to propose a method to measure the emergence of Informational Boundary Spanners (IBSs) and their effectiveness in fostering inter-group information exchange. Further, a novel Agent-Based Modelling (ABM) framework was introduced to systematically study mechanisms that lead to the emergence of IBSs. The proposed method and ABM are then used to create new insight into one specific mechanisms that explain the emergence of IBSs in volatile environments: i.e, learning.

Our results show that learning leads to the emergence of effective IBSs when the information needed has a relatively stable origin (i.e., it is consistently provided by the same node in the network). Further, a highly turbulent and volatile environment can easily lead to informational overload. In this situation, retrieving and sharing all relevant information needed becomes challenging. This chapter shows that the availability of several contacts (here 20 or more) that can share information across the groups is essential for facilitating the emergence of more IBSs, which helps distribute the load of inter-group information exchange and improves the effectiveness of such exchange. Moreover, when the inter-group contacts are numerous (20 or more), and the level of environmental turbulence is high (above 10 disruptive events per day), the performance of IBSs in facilitating inter-group information exchange is increased with learning.

Implications of this study include the possibility to use the proposed method and ABM framework to investigate and understand mechanisms for the emergence of informational boundary spanning from an actor-centred perspective through a combination of case study research and agent-based simulation. By introducing such a method, this chapter answers RQ4 (Cf. Table 1.1).

Additionally, in promoting the emergence of IBSs through learning, actors from different groups exhibit collectively intelligent behaviour by choosing agents that effectively facilitate information exchange across groups (thereby supporting coordinated self-organisation). Further, this collective intelligence is contingent on the volatility of the environment and requires stable sources of information and a high density of inter-group ties to be effective. These findings illustrate that not only does coordinated self-organisation support collective intelligence in volatile environments (as discussed in Chapters 1 and 2), but also that, under the right conditions, collective intelligence can in turn foster coordinated self-organisation in such environments (e.g., by encouraging the emergence of effective inter-group information exchange).

Policy implications of this research consist of the need to (a) collect and summarize information from unstable origins (e.g., via crowdsourcing) and release such information from stable sources so that agents can learn where to find the information they need and (b) build and maintain trusted connections among groups to ensure collectively intelligent behaviour and effective inter-group information exchange, and support coordinated self-organisation even for high levels of volatility.

Further research will focus on investigating the interplay between the emergence of boundary spanning, learning, and the use of information technology, strategic information exchange behaviour (e.g. spread of misinformation, obfuscation, and persuasion to share back), and the formation of information exchange bubbles and fragmentation.

REFERENCES

[1] V. Nespeca, T. Comes, and F. Brazier. “Learning to connect in action: Measuring and understanding the emergence of boundary spanners in volatile times”. In: *arXiv preprint* (Under review). url: https://arxiv.org/abs/2405.11998.

[2] F. H. Norris, S. P. Stevens, B. Pfefferbaum, K. F. Wyche, and R. L. Pfefferbaum. “Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness”. In: *American Journal of Community Psychology* 41.1-2 (Mar. 2008). Read, pp. 127–150. issn: 1573-2770. doi: 10.1007/s10464-007-9156-6.

[3] T. W. Malone. *Superminds: The surprising power of people and computers thinking together*. Little, Brown Spark, 2018.

[4] J. Rockström, A. V. Norström, N. Matthews, R. Biggs, C. Folke, A. Harikishun, S. Huq, N. Krishnan, L. Warszawski, and D. Nel. “Shaping a resilient future in response to COVID-19”. In: *Nature Sustainability* 6.8 (2023), pp. 897–907.

[5] D. Perrone, M. M. Rohde, C. Hammond Wagner, R. Anderson, S. Arthur, N. Atume, M. Brown, L. Esaki-Kua, M. Gonzalez Fernandez, K. A. Garvey, *et al.* “Stakeholder integration predicts better outcomes from groundwater sustainability policy”. In: *Nature Communications* 14.1 (2023), p. 3793.

[6] J. Flack, P. Ipeirotis, T. W. Malone, G. Mulgan, and S. E. Page. “Editorial to the Inaugural Issue of Collective Intelligence”. In: *Collective Intelligence* 1.1 (2022), p. 26339137221114179.

[7] M. Galesic, D. Barkoczi, A. M. Berdahl, D. Biro, G. Carbone, I. Giannoccaro, R. L. Goldstone, C. Gonzalez, A. Kandler, A. B. Kao, *et al.* “Beyond collective intelligence: Collective adaptation”. In: *Journal of the Royal Society interface* 20.200 (2023), p. 20220736.

[8] N. E. Leonard and S. A. Levin. “Collective intelligence as a public good”. In: *Collective Intelligence* 1.1 (2022), p. 26339137221083293.

[9] R. H. Ballou. “The evolution and future of logistics and supply chain management”. In: *European business review* 19.4 (2007), pp. 332–348.

[10] T. W. Malone and K. Crowston. “The Interdisciplinary Study of Coordination”. In: *ACM Computing Surveys* 26.1 (Mar. 1994), pp. 87–119. issn: 0360-0300. doi: 10.1145/174666.174668.

[11] P. Fiala. “Information sharing in supply chains”. In: *Omega* 33.5 (2005), pp. 419–423.

[12] N. Kapucu. “Interorganizational coordination in dynamic context: Networks in emergency response management”. In: *Connections* 26.2 (2005), pp. 33–48.

[13] N. Bharosa, J. Lee, and M. Janssen. “Challenges and obstacles in sharing and coordinating information during multi-agency disaster response: Propositions from field exercises”. en. In: *Information Systems Frontiers* 12.1 (Mar. 2010), pp. 49–65. issn: 1387-3326, 1572-9419. doi: 10.1007/s10796-009-9174-z.

[14] T. Comes, B. Van de Walle, and L. Van Wassenhove. “The coordination-information bubble in humanitarian response: theoretical foundations and empirical investigations”. In: *Production and Operations Management* 29.11 (2020), pp. 2484–2507.

[15] M. L. Tushman. “Special boundary roles in the innovation process”. In: *Administrative science quarterly* (1977), pp. 587–605.

[16] N. Bharosa and M. Janssen. “Principle-Based Design: A Methodology and Principles for Capitalizing Design Experiences for Information Quality Assurance”. en. In: *Journal of Homeland Security and Emergency Management* 12.3 (Jan. 2015). issn: 1547-7355, 2194-6361. doi: 10.1515/jhsem-2014-0073.

[17] D. G. Ancona and D. F. Caldwell. “Bridging the boundary: External activity and performance in organizational teams”. In: *Administrative science quarterly* (1992), pp. 634–665.

[18] N. Kapucu. “Interagency communication networks during emergencies: Boundary spanners in multiagency coordination”. In: *The American review of public administration* 36.2 (2006), pp. 207–225.

[19] A. Zagorecki, K. Ko, and L. K. Comfort. “Interorganizational Information Exchange and Efficiency: Organizational Performance in Emergency Environments”. In: *JASSS* 13.3 (2009), p. 3. issn: 1460-7425.

[20] J. A. Marrone. “Team boundary spanning: A multilevel review of past research and proposals for the future”. In: *Journal of management* 36.4 (2010), pp. 911–940.

[21] N. Altay and R. Pal. “Information Diffusion among Agents: Implications for Humanitarian Operations”. In: *Production and Operations Management* 23.6 (Dec. 2013), pp. 1015–1027. issn: 1059-1478. doi: 10.1111/poms.12102.

[22] N. Altay and M. Labonte. “Challenges in humanitarian information management and exchange: evidence from Haiti”. In: *Disasters* 38.s1 (2014), S50–S72.

[23] I. Van Meerkerk and J. Edelenbos. “The effects of boundary spanners on trust and performance of urban governance networks: findings from survey research on urban development projects in the Netherlands”. In: *Policy Sciences* 47 (2014), pp. 3–24.

6

[24] N. Levina and E. Vaast. “The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems”. In: *MIS quarterly* (2005), pp. 335–363.

[25] J. A. Marrone, P. E. Tesluk, and J. B. Carson. “A multilevel investigation of antecedents and consequences of team member boundary-spanning behavior”. In: *Academy of Management Journal* 50.6 (2007), pp. 1423–1439.

[26] H. Lifshitz-Assaf. “Dismantling knowledge boundaries at NASA: The critical role of professional identity in open innovation”. In: *Administrative science quarterly* 63.4 (2018), pp. 746–782.

[27] C. Adam and B. Gaudou. “Modelling Human Behaviours in Disasters from Interviews: Application to Melbourne Bushfires”. In: *JASSS* 20.3 (2017), p. 12. issn: 1460-7425.

[28] P. Antosz, T. Szczepanska, L. Bouman, J. G. Polhill, and W. Jager. “Sensemaking of causality in agent-based models”. In: *IJSRM* (2022), pp. 1–11.

[29] P. Tubaro and A. A. Casilli. ““An Ethnographic Seduction”: How Qualitative Research and Agent-based Models can Benefit Each Other”. In: *Bulletin of Sociological Methodology/Bulletin de Méthodologie Sociologique* 106.1 (2010), pp. 59–74.

[30] B. Castellani, P. Barbrook-Johnson, and C. Schimpf. “Case-based methods and agent-based modelling: bridging the divide to leverage their combined strengths”. In: *IJSRM* 22.4 (2019), pp. 403–416.

[31] M. T. Hansen. “The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits”. In: *Administrative science quarterly* 44.1 (1999), pp. 82–111.

[32] J. N. Cummings. “Work groups, structural diversity, and knowledge sharing in a global organization”. In: *Management science* 50.3 (2004), pp. 352–364.

[33] W. Van Osch, C. Steinfield, and Y. Zhao. “Towards behavioral measures of boundary spanning success: The effectiveness and efficiency of team boundary spanning in enterprise social media”. In: *Research Papers* (June 2016).

[34] H. Aldrich and D. Herker. “Boundary spanning roles and organization structure”. In: *Academy of management review* 2.2 (1977), pp. 217–230.

[35] J. K. Hazy, B. F. Tivnan, and D. R. Schwandt. “The Impact of Boundary Spanning on Organizational Learning: Computational Explorations”. In: *Emergence* 5.4 (Dec. 2003), pp. 86–123. issn: 1521-3250. doi: 10.1207/s15327000em0504_7.

[36] P. R. Lawrence and J. W. Lorsch. *Organization and environment managing differentiation and integration*. 1967.

[37] R. B. Duncan. “Characteristics of organizational environments and perceived environmental uncertainty”. In: *Administrative science quarterly* (1972), pp. 313–327.

[38] N. Levina and E. Vaast. "Turning a community into a market: A practice perspective on information technology use in boundary spanning". In: *Journal of Management Information Systems* 22.4 (2006), pp. 13–37.

[39] J. N. Sutton, L. Palen, and I. Shklovski. "Backchannels on the front lines: Emergent uses of social media in the 2007 Southern California Wildfires". English. In: *5th International Conference on Information Systems for Crisis Response and Management (Proceedings of ISCRAM 2008)* (2008). Ed. by F. Fiedrich and B. A. van de Walle. Publisher: Information Systems for Crisis Response and Management, ISCRAM, pp. 624–631. issn: 9780615206.

[40] N. Altay and W. G. Green III. "OR/MS research in disaster operations management". In: *European journal of operational research* 175.1 (2006), pp. 475–493.

[41] B. Van de Walle, B. Brugghemans, and T. Comes. "Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination". In: *IJHCS* 95 (2016), pp. 66–79.

[42] T. Comes. "Cognitive biases in humanitarian sensemaking and decision-making lessons from field research". In: *2016 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*. IEEE. 2016, pp. 56–62.

[43] H. Z. Abidin, H. Andreas, I. Gumilar, Y. Fukuda, Y. E. Pohan, and T. Deguchi. "Land subsidence of Jakarta (Indonesia) and its relation with urban development". In: *Natural hazards* 59 (2011), pp. 1753–1771.

[44] H. Abidin, H. Andreas, I. Gumilar, and I. Wibowo. "On correlation between urban development, land subsidence and flooding phenomena in Jakarta". In: *Proceedings of IAHS* 370 (2015), pp. 15–20.

[45] L. Fleming and D. M. Waguespack. "Brokerage, boundary spanning, and leadership in open innovation communities". In: *Organization science* 18.2 (2007), pp. 165–180.

[46] N. Bharosa. "Netcentric information orchestration: assuring information and system quality in public safety networks." en. OCLC: 840441830. PhD thesis. Oisterwijk: BOXPress, 2011.

[47] R. Lindgren, M. Andersson, and O. Henfridsson. "Multi-contextuality in boundary-spanning practices". In: *Information Systems Journal* 18.6 (2008), pp. 641–661.

[48] R. Scott. *Organizations: Rational, Natural, and Open Systems. Prentice-Hall, Englewood Cliffs*. 1992.

[49] J. Watts, R. E. Morss, C. M. Barton, and J. L. Demuth. "Conceptualizing and implementing an agent-based model of information flow and decision making during hurricane threats". In: *Environmental Modelling & Software* (2019), p. 104524. issn: 1364-8152. doi: 10.1016/j.envsoft.2019.104524.

6

[50] V. Nespeca, T. Comes, and L. Alfonso. "Information Sharing and Coordination in Collaborative Flood Warning and Response Systems". en. In: *ISD 2018 Conference Proceedings*. Aug. 2018.

[51] H. A. Simon. "A behavioral model of rational choice". In: *The quarterly journal of economics* (1955), pp. 99–118.

[52] J. M. Epstein and R. Axtell. *Growing artificial societies: social science from the bottom up*. Brookings Institution Press, 1996.

[53] A.-L. Barabási and R. Albert. "Emergence of scaling in random networks". In: *science* 286.5439 (1999), pp. 509–512.

[54] Y. Kreiss, O. Merin, K. Peleg, G. Levy, S. Vinker, R. Sagi, A. Abargel, C. Bartal, G. Lin, A. Bar, *et al. Early disaster response in Haiti: the Israeli field hospital experience*. 2010.

[55] C. Bode and J. R. Macdonald. "Stages of supply chain disruption response: Direct, constraining, and mediating factors for impact mitigation". In: *Decision Sciences* 48.5 (2017), pp. 836–874.

[56] D. H. P. C. C. (DHPC). *DelftBlue Supercomputer (Phase 1)*. https://www.tudelft.nl/dhpc/ark:/44463/DelftBluePhase1. 2022.

[57] R. J. Sternberg, W. Salter, *et al.* "Conceptions of intelligence". In: *Handbook of human intelligence* 1 (1982), pp. 3–28.

[58] L. Argote. "Input uncertainty and organizational coordination in hospital emergency units". In: *Administrative science quarterly* (1982), pp. 420–434.

[59] G. M. Wittenbaum, S. I. Vaughan, and G. Strasser. "Coordination in task-performing groups". In: *Theory and research on small groups* (2002), pp. 177–204.

[60] T. W. Malone and M. S. Bernstein. *Handbook of collective intelligence*. MIT press, 2022.

[61] R. Duncan. "What is the right organization structure? Decision tree analysis provides the answer". In: *Organizational dynamics* 7.3 (1979), pp. 59–80.

[62] T. Holderness and E. Turpin. "From social media to geosocial intelligence: Crowdsourcing civic co-management for flood response in Jakarta, Indonesia". In: *Social media for government services* (2015), pp. 115–133.

[63] T. Claridge. "Functions of social capital–bonding, bridging, linking". In: *Social capital research* 20.1 (2018), pp. 1–7.

[64] R. L. Hawkins and K. Maurer. "Bonding, bridging and linking: How social capital operated in New Orleans following Hurricane Katrina". In: *British Journal of Social Work* 40.6 (2010), pp. 1777–1793.

[65] D. P. Aldrich and M. A. Meyer. "Social capital and community resilience". In: *American behavioral scientist* 59.2 (2015), pp. 254–269.

[66] J. Tasic and S. Amir. "Informational capital and disaster resilience: the case of Jalin Merapi". In: *Disaster Prevention and Management* (2016).

[67] T. J. Pettit, J. Fiksel, and K. L. Croxton. “Ensuring supply chain resilience: development of a conceptual framework”. In: *Journal of business logistics* 31.1 (2010), pp. 1–21.

[68] X. Jia, M. Chowdhury, G. Prayag, and M. M. Hossan Chowdhury. “The role of social capital on proactive and reactive resilience of organizations post-disaster”. In: *IJDRR* 48 (2020), p. 101614. issn: 2212-4209. doi: https://doi.org/10.1016/j.ijdrr.2020.101614.

[69] I. Gölgeci and O. Kuivalainen. “Does social capital matter for supply chain resilience? The role of absorptive capacity and marketing-supply chain management alignment”. In: *Industrial Marketing Management* 84 (2020), pp. 63–74.

[70] A. Agger and J. O. Jensen. “Area-based initiatives—and their work in bonding, bridging and linking social capital”. In: *European Planning Studies* 23.10 (2015), pp. 2045–2061.

[71] Y. Tim, S. L. Pan, P. Ractham, and L. Kaewkitipong. “Digitally enabled disaster response: the emergence of social media as boundary objects in a flooding disaster”. In: *Information Systems Journal* 27.2 (2017), pp. 197–232.

[72] W. Van Osch and C. W. Steinfield. “Team boundary spanning: Strategic implications for the implementation and use of enterprise social media”. In: *Journal of Information Technology* 31 (2016), pp. 207–225.

[73] C. Heavey, Z. Simsek, C. Kyprianou, and M. Risius. “How do strategic leaders engage with social media? A theoretical framework for research and practice”. In: *Strategic Management Journal* 41.8 (2020), pp. 1490–1527.

[74] D. G. Ancona and D. Caldwell. “Beyond boundary spanning: Managing external dependence in product development teams”. In: *The Journal of High Technology Management Research* 1.2 (1990), pp. 119–135.

[75] J. Wolbers, K. Boersma, and P. Groenewegen. “Introducing a fragmentation perspective on coordination in crisis management”. In: *Organization Studies* 39.11 (2018), pp. 1521–1546.

7 Discussion and conclusion

Supporting resilience through collective intelligence during disasters relies on the coordination and self-organisation of the multiple organisations and groups operating, including professional response organisations and communities. This coordinated self-organisation requires the exchange of timely and relevant information within and across groups. Supporting effective disaster information sharing is, however, challenging given the rapidly changing and uncertain environment and the associated high information load. In disaster response, actors adapt through self-organisation in the form of swift and unpredictable changes in organisational patterns and information needs. Therefore, information flows need to continually adapt to provide the information needed to those who need it while avoiding information overload.

This dissertation took an actor-centred perspective to disaster information sharing that accounts for these challenges when studying a system's ability to support coordinated self-organisation. This chapter presents the discussion and conclusion of such research. It begins by re-assessing the research questions, then illustrates the contributions of this thesis, and finally suggests avenues for future research.

7.1. Re-assessing research questions

The overarching research question posed by this thesis was: *How can actor-centred disaster information sharing that supports coordinated self-organisation be systematically analysed?*

This question was answered by dividing it into three sub-questions. In the following, each of these sub-questions is discussed.

7.1.1. RQ1: developing conceptual framework for actor-centred disaster information sharing

The first sub-question to be answered was: *Can an actor-centred framework be designed to capture the characteristics and requirements for disaster information sharing that supports coordinated self-organisation, and how?*

Chapter 3 provided the methodological steps necessary to design conceptual frameworks (and their characteristics and requirements) that enable the study of a phenomenon of interest from an actor-centred perspective. Chapter 4 applied the methodological steps from Chapter 3 to the phenomenon of ACDIS. First, the Chapter carried out a literature review, resulting in a list of *characteristics* of ACDIS. Based on these characteristics, the requirements for ACDIS were designed. These requirements were validated and refined through the case study of Jakarta, Indonesia. The validated and refined requirements informed the design of an actor-centred conceptual framework for studying disaster information sharing. The resulting framework is illustrated in Figure 7.1.

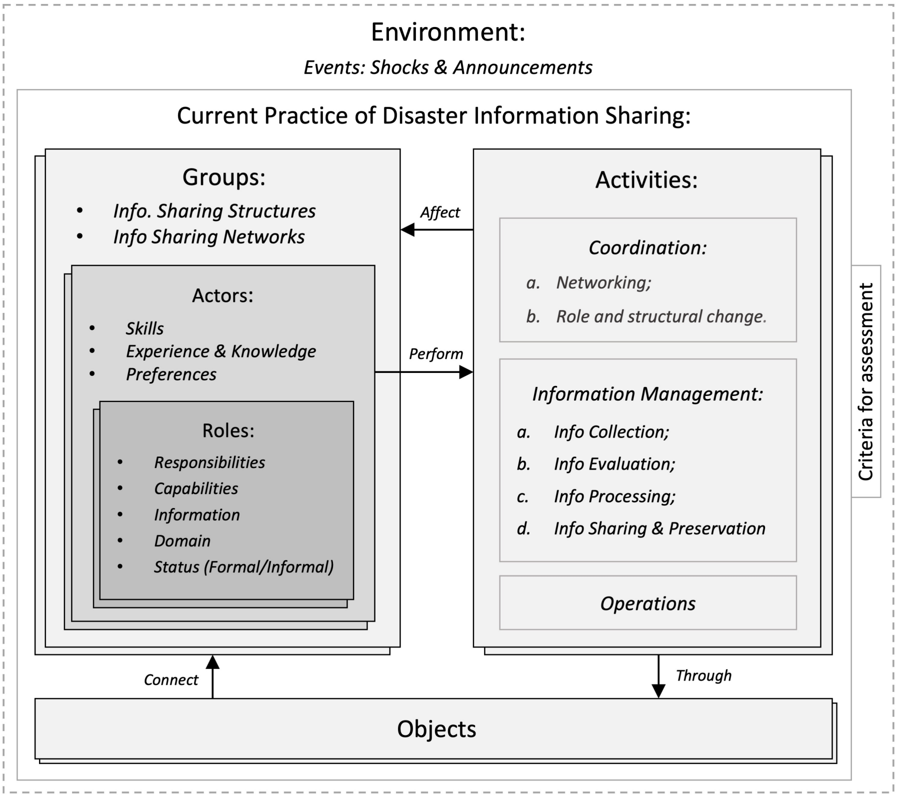

Figure 7.1: Actor-centred framework for the analysis of the configuration of the current practice of disaster information sharing, its potentially self-organized changes, and its performance measured through the criteria for assessment. These criteria measure the extent to which the current practice supports coordinated self-organisation through information by looking at information quality (relevance, timeliness, reliability, verifiability, and accessibility), and load.

Chapter 5 validated this framework in terms of its ability to enable the study of ACDIS with the case of Jakarta. The framework enabled this study in three steps: analysis of configuration of the current practice of disaster information sharing, analysis of change in the configuration (including self-organized change), and analysis of performance (i.e., the system's ability to support coordinated self-organisation). The analysis of configuration identified the key actors, their groups, roles, and information-sharing activities during disaster response in Jakarta. The analysis of change showed how roles could change through emergent, self-organized processes based on individual information-sharing activities (e.g., in the case of IBSs emergence). The analysis of performance analysis revealed the adequacy of Jakarta's response and highlighted areas for improvement, such as information relevance.

The proposed conceptual framework was further validated in an independent study by [1], conducted in the Bospolder-Tussendijken neighborhood of Rotterdam during the COVID-19 pandemic. This study showed that the conceptual framework provided the means to analyse system configurations, changes, and performance in fostering coordinated self-organisation, offering valuable insights for urban resilience policy.

7.1.2. RQ2: Developing ABMs of actor-centred disaster information sharing

The second sub-question to be addressed in this thesis was: *Can an ABM be developed for supporting the study of actor-centred disaster information sharing across groups, and how?*

ACDIS considers how micro-level behaviours of individual actors, along with their *potential* interactions with meso-level group characteristics and macro-level environmental and institutional factors, shape inter-group information exchange during disasters (Cf. Section 1.3).

Chapter 5 answered RQ2 by developing an empirical ABM to study ACDIS between the Marunda community and professional response organisations in Jakarta, Indonesia. This ABM facilitated the study of ACDIS across these two groups in two key ways. First, it enabled an exploration of disaster information sharing dynamics from an actor-centred perspective by distinguishing two types of information needs in the ABM: known and latent. Latent information needs arise when actors are unaware of certain information needs. This significantly affects the actors' information-sharing behaviour at the micro-level, as actors cannot actively seek information they do not recognize they need. Simulations with the ABM show that latent information needs and the resulting behaviours impact the effectiveness of inter-group information exchange, reducing the amount of relevant and timely information reaching those in need and thus resulting in higher information gaps (Cf. Section 5.8.1).

Second, the ABM provided a description of the considered case by synthesizing and rigorously formalizing knowledge from the case and previously available literature and ABMs [2]. This formalization provided a foundation for further research on ACDIS. Specifically, the model developed in Chapter 5 served as the foundation for the theoretical ABM used in Chapter 6. This new ABM facilitated the study of ACDIS across groups through IBSs. Simulation results obtained through this model revealed that when actors learn to identify providers of high-quality information, this leads to the emergence of IBSs that more effectively convey information across groups compared to scenarios where learning is absent. This process depends on environmental volatility — comprising environmental uncertainty and turbulence — and on the availability of inter-group ties. Notably, the emergence of effective IBSs through learning occurs when environmental uncertainty is low (i.e., with stable information sources) and, in conditions of high environmental turbulence, relies on a high number of inter-group ties.

By demonstrating the impact of micro-level behaviours (i.e., learning) and their interplay with macro-level factors (i.e., inter-group ties and environmental volatility) on inter-group information exchange, these findings provide an actor-centred perspective on disaster information sharing. This supports the conclusion that this thesis addresses RQ2 by developing ABMs for the study of ACDIS. It also shows that the descriptive ABM developed in Chapter 5 established a foundation for future studies on ACDIS across groups.

7.1.3. RQ3: Designing a methodology for ABM development

The third sub-question to be answered was: *Can a methodology be designed to develop ABMs for supporting the study of a phenomenon of interest through qualitative inquiry, and how?*

Chapters 3-5 contributed to addressing this research question, as discussed in the following. Chapter 3 laid the foundations for addressing this question by developing a methodology to study a phenomenon of interest using ABMs developed through qualitative case study research. The methodology aims to balance cross-case comparability with the flexibility to capture different cases, while also providing the versatility needed for developing ABMs for various theoretical and empirical modelling purposes, all while maintaining rigour. The resulting methodology is composed of two phases. In the first phase a conceptual framework tailored to a specific phenomenon of interest is developed. In the second phase, an ABM is developed based on the conceptual framework and generic models as shown in Figure 7.2.

Chapters 4 and 5, through the Jakarta case study, demonstrated the effectiveness of the proposed methodology in rigorously translating qualitative data into an empirical ABM, while balancing cross-case comparability and flexibility. First, *rigour* was maintained through the structured and systematic (a) development of a conceptual framework tailored to the phenomenon of ACDIS based on qualitative research (Chapter 4) and (b) interpretation of qualitative data via the conceptual framework and the GAM generic model (Chapter 5).

Second, this methodology maintained a degree of *comparability* across the case study of Jakarta and possible future case studies by prescribing to consistently centre the analysis of each case on the same conceptual framework tailored to the phenomenon of ACDIS (developed in Chapter 4). While the consistent use of this

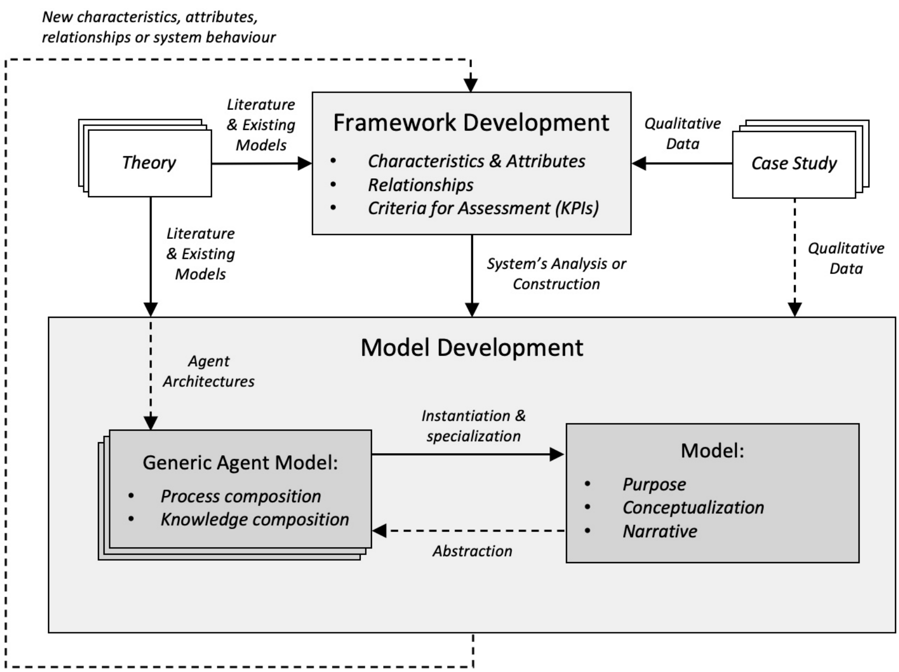

Figure 7.2: Methodology for developing ABMs through qualitative inquiry to study a phenomenon of interest while balancing cross-case comparability and flexibility, and ensuring versatility.

framework ensures a level of cross-case comparability, the adoption of different generic models for different cases limits the extent of this comparability. This is because, while each case is interpreted through the same conceptual framework, it may be analysed using different generic models depending on the specific case.

Additionally, the methodology offered some *flexibility* to study the novel phenomenon of ACDIS by allowing the development of a new conceptual framework tailored to this phenomenon (Chapter 4) and the selection of a suitable generic model (GAM) for the specific case of Jakarta (Chapter 5). Flexibility was provided only to a degree as the common conceptual framework provides a level of constraint across all cases. In sum, while not as flexible as case-based methodologies that derive agent rules without considering any framework, or as comparable as framework-based methodologies that employ the same framework across all cases, this methodology enabled to strike a balance between the two while maintaining rigour.

In sum, when the objective is to capture the characteristics of a single case (e.g., to support decision-making) flexibility becomes essential, while comparability is secondary. In these situations, case-based methods are the most suitable choice (see, i.e., [3, 4]). Conversely, when comparability is necessary and flexibility is not a priority, framework-based methods are preferable. This applies, for instance, when studying a phenomenon for which an existing framework, including an agent architecture, is available to analyse cases and compare results across them (see, i.e., [5, 6]). Finally, the methodology proposed in this dissertation is particularly well-suited when both comparability and flexibility are required to some extent. This applies when investigating a novel phenomenon of interest (e.g., ACDIS), where comparability is essential for comparing results across cases, while flexibility is critical due to the absence of established frameworks or specific agent architectures given the novelty of the phenomenon. In such situations, the proposed methodology allows for the development of a conceptual framework tailored to the phenomenon of interest and supports the selection, comparison, and potential design of generic models incorporating agent architectures suited to the phenomenon..

The methodology was also found to be *versatile*, providing a means to develop an empirical descriptive ABM (Chapter 5) and outlining steps for developing theoretical ABMs (Chapter 3). Although this thesis does not illustrate the development of a theoretical ABM through a specific application of the methodology, as it does for descriptive ABMs, Chapter 6 presents a theoretical ABM developed by abstracting from the empirical model in Chapter 5. This model was developed by following the methodology, even though its development process is not explicitly detailed in Chapter 6. Nevertheless, the procedural steps for developing a theoretical ABM are provided in Chapter 3.

7.1.4. RQ4: Measuring and understanding the actor-centred emergence of IBSs

7

The fourth sub-question to be answered was: *Can a quantitative method be designed to measure and understand the emergence of effective informational boundary spanners from an actor-centred perspective, and how?*

Chapter 6 addressed this question by developing a method to measure the emergence of effective IBSs from an actor-centred perspective. ACDIS focuses on the impact of micro-level behaviour (i.e., the behaviour of individual actors) and its potential interplay with meso- and macro-level factors on inter-group disaster information exchange. Therefore, it is essential that an actor-centred method captures the emergence of individual actors as IBSs, rather than studying such emergence at the group level. Focusing on the micro level allows for examining its interplay with other levels and their impact on inter-group information exchange.

The method introduced in this thesis identifies emergent IBSs based on the total number of times an actor performs the informational boundary spanning function by providing new and relevant external information to a group in need. A threshold defines the minimum number of times an actor must perform this function to be considered an emergent IBS. An adequate threshold for measuring the emergence of effective IBSs is one that identifies those contributing to enhanced system performance, with performance measured by the percentage of external information required by groups that is successfully obtained. Since multiple thresholds within a range can meet this condition, the emergence of IBSs is studied across this range of thresholds rather than relying on a single one. The consistency of findings is then assessed across multiple thresholds within this range.

Chapter 6 also developed an ABM of disaster information exchange. This ABM was then used to test if the proposed method provides the means to (a) measure the emergence of IBSs that effectively convey information across groups, and (b) understand mechanisms leading to the emergence of IBSs. This ABM captures a potential mechanism for the emergence of IBSs found in Chapter 5 - i.e., learning who provides high quality information and adjusting information sharing preferences accordingly.

The analysis of this ABM's results through the proposed method provided two conclusions. Firstly, the method enabled the measurement of the emergence of IBSs, identifying the individual actors who effectively convey information across groups and contribute to overall system performance. This was evidenced by consistent findings across various adequate thresholds. However, the results also suggested the importance of considering a wide range of adequate thresholds to verify result consistency and determine if any inconsistencies are outliers or if conclusions should be revised based on these inconsistencies.

Secondly, the findings demonstrated that the method can be effectively combined with an ABM to study the emergence of IBSs. Specifically, this approach enabled the examination of whether the learning mechanism leads to the emergence of IBSs. First, insights from the Jakarta case study (Chapter 5) and existing literature were used for theory building, specifically to formulate propositions regarding IBS emergence. These propositions were then tested using the ABM and the method, which enabled the simulation and measurement of IBS emergence.

The results supported the propositions, showing that when actors learn to identify high-quality information sources, they collectively select IBSs who enhance inter-group information exchange, thereby improving overall system performance. This collective intelligence occurs in both low-volatility environments with stable information sources and high-volatility environments with sufficient inter-group connections, as the propositions suggested.

In practice, in this increasingly complex and chaotic world characterized by growing volatility, information often originates from unstable sources. Therefore, to foster the emergence of effective IBS, it is crucial to gather information from unstable sources (e.g., via crowdsourcing techniques) and share it widely via stable sources to help actors collectively identify high-quality information providers through learning. Additionally, building and maintaining numerous trusted connections between different groups, such as professional response organisations and communities, is essential to distribute the information load evenly and thus improve the effectiveness of inter-group information exchange, even at high levels of volatility.

These findings illustrate how the combined use of the method and an ABM framework enables researchers to measure and understand the emergence of IBSs, including the conditions that either favour or hinder this emergence. Understanding these conditions also leads to practical insights concerning information sharing strategies aimed at fostering the emergence of IBSs, thereby supporting coordinated self-organisation and resilience.

7.2. Contributions

This thesis set to study disaster information sharing through an actor-centred perspective, with the goal of supporting coordinated self-organisation, collective intelligence, and resilience in disaster response operations involving communities and professional response organisations. The thesis integrates several disciplines, such as crisis and disaster management, information management, and complex systems modelling and simulation. As such, its contributions can be of interest for researchers in these and related fields.

The contributions of this thesis include methodologies and methods to study actor-centred information sharing through a combination of qualitative case study research and ABMs, ABMs, and theoretical insights in ACDIS. In sum, the key contributions of this thesis are:

1. Methodologies and methods:

    - **Methodology to develop ABMs to study a phenomenon of interest based on qualitative case study research** (Chapter 5, 6). Compared to existing methodologies that prioritize either cross-case comparability or flexibility to capture different cases, this approach enables researchers to balance both, while maintaining analytical rigour. This methodology is also novel in that it enables the versatility to support both theoretical and empirical model development. The process begins with the construction of a conceptual framework centred on a specific phenomenon of interest. This framework, combined with a generic agent architecture, is then used to develop an empirical or theoretical ABM to study the phenomenon of interest (e.g., ACDIS). For empirical applications, the framework and generic model are used to structure and interpret qualitative data from case study research and translate it into an ABM in a systematic and transparent manner. For theoretical modelling, the framework and generic models provide templates for designing the agents, their interactions, behavioural rules, and performance indicators. This methodological versatility allows for theoretical models to be used in developing and inspecting propositions through simulation (e.g., Chapter 6), which could then inform the design of empirical studies aimed at validating or refining those propositions. Conversely, empirical models can be used to capture rich, context-specific insights (e.g., Chapter 5), informing future research and potentially contributing to explanatory theory-building through case study analysis. In this way, the methodology serves a dual purpose: it acts as a vehicle for developing, inspecting, and refining theories prior to empirical testing, and also functions as an empirical tool for learning from case studies. When combined with the ability to balance cross-case comparability and contextual flexibility, this versatility supports the *integrated use of ABMs and multiple case studies*. Theoretical models can be used to develop and refine propositions, which then inform the selection of research questions and case studies. These theoretical frameworks can be systematically applied to each case and, when necessary, flexibly adapted in response to empirical findings. When such frameworks are applied consistently and not overly modified across cases, they allow for the use of a replication logic. This makes it possible to test, confirm, extend, refine, or refute theoretical propositions across a variety of cases to further the understanding of a phenomenon of interest.

- **Method to measure the emergence of IBSs** at the micro-level (Chapter 6). Unlike methods that examine the emergence of IBSs at the group level, the approach introduced in this thesis offers the resolution necessary to pinpoint individual IBSs. Once the individual IBSs are identified, it is possible to consider the interplay between their individual characteristics and behaviour at the micro level (e.g., network centrality of IBS candidates), information exchange networks at the meso level (e.g., number of inter-group ties), and environmental characteristics such as environmental volatility at the macro level. This approach helps to understand how factors at different levels foster or hinder the emergence of IBSs that effectively convey information across groups. In this dissertation, the method was combined with agent-based modelling and simulation given its ability to capture complex interactions between the micro, meso, and macro levels. However, adapted versions of this method may also be combined with other research methods, such as controlled behavioural experiments or big data analytics (e.g., social media feeds), to study the emergence of IBSs.

2. Agent-based models (chapter 5 and 6). Two ABMs were developed in this thesis that enable to study disaster information sharing from an actor centred perspective.

   - **Empirical ABM** of actor-centred information exchange in the Marunda community of north Jakarta (Chapter 5). This model represents a non-reductionist description [2] of the case of Jakarta, specifically of the Marunda Community. The model aims to capture the way information is exchanged within and across communities and professional response organisations during the response to floods in this specific case. It was developed based on findings obtained through the collection and analysis of interviews and focus groups, previous studies, and technical documents (e.g., evacuation plans) from the considered area. This ABM can be used by researchers and practitioners to explore the functioning of disaster information sharing from an actor-centred perspective in the specific case of Marunda. It can also be modified to explore the potential implications of alternative interventions aimed at improving inter-group information exchange during the response to floods.

- **Theoretical ABM** of actor-centred disaster information exchange (Chapter 6). Unlike previously developed models that either fix the number of IBSs instead of examining their emergence, or focus solely on network-level characteristics without identifying individual actors who span boundaries and convey relevant information across groups, this ABM takes a different approach. It enables, in combination with the method described above, micro-level analysis of the mechanisms leading to the emergence of effective IBSs. This emergence can be studied under varying conditions, including the presence or absence of learning, and across different levels of environmental volatility and intergroup connectivity. In doing so, the model offers a means to explore the conditions that foster the emergence of IBSs and support coordinated self-organization in disaster response.

3. Theoretical insights in ACDIS (chapter 4 and 6):

   - **Conceptualization of disaster information sharing from an actor-centred perspective through the framework** (Chapter 4). This conceptual framework enables the study of disaster information sharing from an actor-centred perspective in three steps: analysis of the configuration of disaster information sharing (i.e., the actors, groups, roles in place, and how they exchange information), analysis of the configuration's change through possibly self-organized adaptation processes, and analysis of the performance in terms of the system's ability to support coordinated self-organisation through information. This performance is measured in terms of information quality (i.e., relevance, timeliness, accessibility, interoperability, reliability, and verifiability) and load.

   - **Learning as a collectively intelligent mechanism for IBS emergence** (Chapters 6). This dissertation shows that learning who provides high-quality information constitutes a mechanism leading to the emergence of IBSs that effectively convey information across groups thus supporting coordinated self-organisation (Proposition 1). It also shows that such a mechanism is only helpful for stable sources of information (Proposition 2) and a high number of inter-group ties (Proposition 3). The collective ability to learn best practices, including who is most effective in a particular role, and to adopt such practices (e.g., by selecting and facilitating the emergence of effective IBSs) is a central feature of collective intelligence. As such, collective intelligence plays a key role in fostering coordinated self-organisation and resilience by facilitating the selection and emergence of effective IBSs.

7.3. Implications for practice

This thesis presents the following implications for communities and professional response organisations such as public agencies and NGOs seeking to improve information exchange with other groups during crisis response efforts, thereby supporting their coordinated self-organisation, collective intelligence, and resilience:

- **Empower communities** (Chapter 5). This dissertation illustrated how community members tend to address a greater portion of their information needs, including through external information provided by professionals, compared to the portion of information needs that professionals fulfil, including external information provided by communities. In other words, communities often have a better of understanding of current developments that matter to them compared to professional response organisations. This means that, from a purely informational standpoint, communities tend to be better informed to address local needs. Additionally, being often already located in disaster-affected areas, they can respond more quickly [7]. However, communities frequently lack the skills or knowledge to respond effectively when faced with disaster-induced shocks and disruptions, particularly when response tasks require specialized knowledge and training (e.g., in search and rescue or fire response operations). Furthermore, communities' situational awareness tends to be highly localized, lacking the broader oversight necessary to make decisions that account for the overall disaster response situation. As a result, community actions may inadvertently disrupt professional response efforts due to a lack of oversight, knowledge, or expertise [7, 8]. At the same time, convergence of spontaneously formed volunteer community groups operating either physically or online in disaster affected areas is inevitable and it represents both a challenge for coordination, as well as an opportunity for effective response [7–9]. To foster resilience, governmental agencies and NGOs should focus on empowering communities with the knowledge, skills, and resources to either act effectively on the information they receive [10] or redirect it to those with the necessary expertise and resources, whether within or beyond the community. This includes facilitating the contribution of communities to tasks that align with their available knowledge, skills, and expertise [7, 8]. Additionally, effective disaster response requires merging the highly localized situational awareness of communities across affected areas and combining it with the oversight of professional response organisations. This integration would provide a common operational picture, essential for supporting coordinated efforts that avoid duplication and gaps in disaster response operations [11]. Promising avenues to achieve two-way communication between communities and professional response organisations, enabling the development of such a common operational picture, include the use of crowdsourcing platforms such as Ushahidi and Petabençana [12–15] (with the due limitations, see [16, 17]). In the case of Petabençana, the platform was co-designed with communities and professional response organisations, and training activities were conducted with communities to empower and engage them with the platform.

- **Consider latent information needs** (Chapter 5). This thesis has shown that providing necessary information to actors on time is particularly challenging when they are unaware of their information needs (i.e., when those needs are latent). In such cases, actors cannot actively search for the information they require because they do not know what they need. To address latent information needs, tailored 'push' information sharing strategies should be developed to notify actors directly about relevant information, as opposed to 'pull' strategies where information is accessed on demand [18]. One option might be to broadcast information suspected to address the latent needs of some actors through widely distributed push notifications. However, this approach risks overwhelming actors with excessive, unsolicited information, without filtering out those who do not need it. When widely adopted, such a strategy can lead to information overload, impairing actors' ability to locate the information they need, even when it is available [19, 20]. A more refined approach would involve identifying the latent information needs of actors and pushing information only to those likely to find it relevant. Yet, determining information needs of actors, and whether such needs are latent or not, is challenging[1]. First, information needs depend on a number of factors including the criticality of information (when associated with disruptive events that require immediate action) and the roles assumed by the actors. Establishing these factors is a challenge. For example, roles can shift rapidly and unpredictably during disasters due to self-organisation, making it difficult to map actors' roles and corresponding information needs in real time [22, 23]. New technologies, such as AI and Large Language Models (LLMs), could assist in identifying the roles actors assume (e.g., through their web searches or LLM prompts) and their corresponding information needs. Second, once actors' roles are established, distinguishing between latent and known information needs becomes another challenge. A potential criterion for this distinction could be the novelty and relevance of the information. Disaster events evolve over time, creating both initial occurrences or predictions (in the case of early warnings) and subsequent updates. The initial occurrence or prediction of an event represents a latent information need for actors in roles for which the event is relevant. In contrast, updates on the event could be considered known information needs, as actors, once aware of the event, anticipate further updates. Machine learning algorithms could be employed to detect events based on information shared on social media or crowdsourcing platforms, associate updates with such events, and match event types with roles, thus enabling prediction of the latent and known (non-latent) information needs of actors once their roles are established [23]. Once latent and non-latent needs are identified, information related to known needs could be made accessible through a 'pull' strategy, while information related to latent needs could be 'pushed' directly to the relevant actors. This dual approach would reduce the risk of information

[1] However, in some cases, latent needs can simply be inferred from actors locations (e.g., early warnings for actors in areas expected to be flooded) [13, 21].

overload by limiting unnecessary notifications.

- **Promising information sharing strategies to support coordinated self-organisation** (Chapter 6). This dissertation found two promising ways to support effective information exchange in high levels of environmental volatility. First, it is key to gather information about shocks from unstable information sources (e.g., via crowdsourcing), summarize it, and distribute it widely from a single stable source (e.g. via ICT platforms as smartphone apps, social media accounts, and websites). This helps actors learn where to get the necessary information, and the system to adjust information flows in a collectively intelligent manner so that the information needed reaches those who need it. Second, a high number of inter-group connections was found to be crucial in fostering effective information exchange in volatile environments. Therefore, it is essential that communities and professional response organisations develop and maintain many trusted connections among groups.

7.4. Future research: An agenda on Collective Intelligence for Resilience

The resilient systems of the future will ensure that institutions and societal actors have the capacity to prepare for, withstand, recover, and learn from systemic, compounding, and unpredictable shocks [24–26]. Achieving this goal requires to foster different capacities of resilience, including absorption, adaptation, and transformation; while considering multiple scales in time (e.g., the short, medium, and long term implications of decisions made during crises) and governance (e.g., from the national to the local) [27–32].

One of the lessons learned from this thesis is that, to foster disaster resilience, it is key to support coordinated self-organisation through effective information sharing, for which collective learning and more generally collective intelligence are essential. Collective intelligence is the ability of a group or organisation to solve complex problems in a changing environment [33–35]. Key aspects of collective intelligence include the following collective capabilities of a group [34, 36, 37]:

- Sensing (or observing): detecting and making sense of information regarding relevant environmental changes in a timely manner;
- Remembering: preserving information and knowledge and transferring it from where it is available to where it is needed for coordination and decision making;
- Learning: recognizing and memorizing knowledge such as best practices including who is most effective at carrying out particular roles and adapt accordingly.

From a collective intelligence perspective, this dissertation has shown how collective *learning* supports the individuation and selection of actors that are effective in fostering inter-group information exchange thus improving the groups' (a) *sensing* capability to detect critical changes in their environments and (b) *remembering* capability to transfer information from where it is available to where it is needed. The ability to detect relevant external changes is crucial for the capacities of resilience namely, to absorb shocks by activating an effective response in the short term, and to adapt or transform in the long term [11, 26, 27, 35, 38]. Adaptation and transformation also require collective learning, another key capability of collective intelligence [26, 28, 38, 39]. Additionally, disaster response systems are prone to collectively 'forgetting' knowledge acquired during the response due to high staff turnover and the challenges of transferring knowledge between those leaving and those entering the field. Smarter strategies for collective remembering, such as storing and making information accessible through the use of LLMs [40], could address this challenge. These examples highlight promising synergies between fostering collective intelligence and enhancing resilience. These synergies have been explored mostly in crisis management (see, e.g., [41–45]), particularly with respect to the short-term absorption capacity of resilience. However, the dynamics between collective intelligence and resilience, especially concerning the capacities for adaptation and transformation and their interplay with absorption, remain largely unexplored. As such, a research agenda is proposed in this dissertation focused on studying how Collective Intelligence can support REsilience (CI4RE). This CI4RE agenda includes the following cross-cutting themes. For some themes, detailed research directions directly follow from this dissertation and are discussed within the corresponding theme.

- **Collective intelligence for coordinated self-organisation**. This theme focuses on investigating, through an actor-centred perspective, how collective intelligence can support self-organisation, decision-making, and coordination by enhancing the capability of governmental agencies, NGOs, and communities to collectively: (a) detect and make sense of environmental changes, (b) learn and adapt, and (c) retain and transfer relevant knowledge to where it is needed. This must be achieved while operating in the volatile environment of a crisis, characterized by continual and unpredictable changes, including the constant influx of new actors, groups, and organisations joining disaster response operations (e.g., due to high humanitarian staff turnover and the involvement of spontaneous volunteer community groups). This research theme includes refining and expanding the findings from this dissertation as discussed in the following:

  – Further validation of the conceptual framework for studying disaster information sharing from an actor-centred perspective. While the framework has been developed and validated via two case studies (i.e., Marunda in Jakarta, and Bospolder-Tussendijken in Rotterdam), it requires further validation and refinement. This includes considering environmental complexity, matching the diversity of tasks and information managed by groups during disaster response. Capturing complexity is crucial as it can increase information load, affecting actors' ability to exchange and process information effectively.

  - Further validation of the propositions on the emergence of IBSs through learning. The propositions outlined in this thesis are based on literature, grounded in the Jakarta disaster response case study, and rigorously explored through an agent-based model. However, these results are exploratory and require further investigation and testing to be generalized, involving additional case studies in different volatile environments beyond disaster scenarios. Additionally, controlled behavioural experiments and real-life disaster response simulations could also be employed to systematically test these propositions.
  - Extending the current understanding of IBSs emergence. Several key factors influencing the emergence of effective IBSs require further research. First, the current model considers non-strategic agents, overlooking the impact of personal agendas and strategic behaviours like persuasion, obfuscation, and misinformation. Second, actors that learn and adjust their information exchange preferences can lead to both (a) effective IBSs supporting inter-group information exchange and (b) poor communication leading to fragmentation, with the interplay between these elements remaining unexplored. Third, the assumption of a constant information exchange network ignores the evolving nature of connections formed by boundary spanners, necessitating further research into how networking activities and contact decay impact IBS emergence in volatile environments.

- **Hybrid intelligence**. Information systems and technologies such as social media, crowdsourcing platforms, and AI (including large language models) already shape and show great promise in fostering the collective intelligence of hybrid human-machine systems [22, 40–42, 46–50]. At the same time, these technologies have introduced novel challenges that threaten collective intelligence and resilience, including the spread of misinformation, as well as knowledge homogenization and the unintended introduction of hidden biases in AI-supported decision making [40, 51, 52]. This theme focuses on designing coordination mechanisms that combine information systems, AI agents, and human groups to enable smarter sensing, remembering, and learning, while addressing the challenges introduced by these technologies. The goal is to foster absorption, adaptation, and transformation within disaster response systems. For instance, this theme includes research on collective detection of misinformation on social media to distinguish reliable from unreliable information (sensing), and on using LLMs as tools for collective learning and remembering, with a focus on avoiding knowledge homogenization and bias [40]. This thesis contributed to this theme by advancing the understanding of IBS emergence, offering insights that could enhance inter-group information exchange and collective intelligence through targeted information sharing strategies involving the use of ICT. These strategies include summarizing information from unstable sources via crowdsourcing platforms and consistently providing it from stable sources to help actors learn where to find high-quality information (including its verifiability and reliability) and foster the emergence of IBSs. However, concrete strategies to achieve this in practice remain unexplored and require further research. Further research is also needed to study the interplay between IBS emergence, AI, and ICT, such as traditional and social media, and crowdsourcing platforms, which have been shown to shape the emergence of inter-group information exchange and IBSs [53–55].

- **Combining agent-based modelling and case study research**. This thesis has shown that studying the way collective intelligence can support resilience benefits from the combined use of agent-based modelling and case study research. While some advancements in this theme were made in Chapter 3, best research practices focused on combining these methods are still missing. This research theme focuses on studying the way qualitative and quantitative case study research can complement and be complemented by agent-based modelling. It includes expanding the methodology for ABM development through qualitative inquiry proposed in this dissertation to include quantitative methods to enhance rigour. For instance, model conceptualization and narratives derived from generic models could guide the design of quantitative tools like surveys, allowing for the statistical measurement of actors' choices.

- **Participatory modelling and model-based sensemaking**. The development and use of one or more conceptual and computational models is an essential feature of collective intelligence, illustrating the way a group (e.g., the government) makes sense of and learns from a crisis [36, 37, 56–59]. This theme focuses on fostering the collective intelligence of groups of decision-makers, domain experts, and scientists when making sense of, responding to, and learning from crises [60–64]. It does so by developing and implementing problem structuring techniques involving the participatory development and use of conceptual and computational models and evaluating their impacts on decision making and sensemaking [57, 65]. While participatory modelling is typically limited in terms of group size (up to 15 participants [66]), recent developments in AI and group deliberation tools show promise in up-scaling these techniques [40, 49], which will be further explored in combination with the use of conceptual and computational models in this theme. Further, given that fostering resilience requires considering multiple scales in time and governance, the conceptual and computational models adopted to support resilience should be able to capture such different scales. One single model is often not sufficient to consider the complex interplay among such different scales. The use of multi-models (i.e. combinations of interacting models) is a promising approach to address this challenge [67]. Yet, the participatory techniques necessary to design multi-models in collaboration with groups are currently lacking and are explored in this theme.

As this world struggles to cope with increasingly threatening, pervasive, frequent, and compounding disasters and crises, the quest to enhance disaster resilience becomes paramount. This thesis has demonstrated that harnessing the capabilities of multiple actors and groups to self-organize, coordinate, and act in a collectively intelligent manner is a promising avenue for building disaster resilience. By fostering the collective ability of governments, NGOs, and communities to sense, learn, and remember critical information and knowledge, systems can absorb, adapt, and transform in response to shocks, improving their resilience and better addressing both the challenges of today and those of tomorrow. The insights and methodologies developed in this dissertation, together with this research agenda, indicate a path forward and provide practical tools for communities, organisations, and governments striving to build a more resilient future.

REFERENCES

[1] G. Slingerland, E. Edua-Mensah, M. van Gils, R. Kleinhans, and F. Brazier. “We’re in this together: Capacities and relationships to enable community resilience”. In: *Urban Research & Practice* 0.0 (2022), pp. 1–20. doi: 10.1080/17535069.2022.2036804.

[2] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. “Different Modelling Purposes”. In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[3] S. Bharwani. “Adaptive knowledge dynamics and emergent artificial societies: ethnographically based multi-agent simulations of behavioural adaptation in agro-climatic systems”. In: *University of Kent, UK* (2004).

[4] S. Bharwani, M`. Coll Besa, R. Taylor, M. Fischer, T. Devisscher, and C. Kenfack. “Identifying Salient Drivers of Livelihood Decision-Making in the Forest Communities of Cameroon: Adding Value to Social Simulation Models”. In: *JASSS* 18.1 (2015), p. 3. issn: 1460-7425.

[5] A. Ghorbani, P. Bots, V. Dignum, and G. Dijkema. “MAIA: a Framework for Developing Agent-Based Social Simulations”. In: *JASSS* 16.2 (2013), p. 9. issn: 1460-7425. doi: 10.18564/jasss.2166.

[6] A. Ghorbani, G. Dijkema, and N. Schrauwen. “Structuring Qualitative Data for Agent-Based Modelling”. In: *JASSS* 18.1 (2015), p. 2. issn: 1460-7425.

[7] J. Whittaker, B. McLennan, and J. Handmer. “A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges”. In: *IJDRR* 13 (Sept. 2015), pp. 358–368. issn: 2212-4209. doi: 10.1016/j.ijdrr.2015.07.010.

[8] R. A. Stallings and E. L. Quarantelli. “Emergent citizen groups and emergency management”. In: *Public administration review* 45 (1985), pp. 93–100.

[9] B. McLennan, J. Whittaker, and J. Handmer. “The changing landscape of disaster volunteering: opportunities, responses and gaps in Australia”. In: *Natural Hazards* 84 (2016), pp. 2031–2048.

[10] K. Haynes, D. K. Bird, and J. Whittaker. “Working outside ‘the rules’: Opportunities and challenges of community participation in risk reduction”. en. In: *IJDRR* 44 (Apr. 2020), p. 101396. issn: 2212-4209. doi: 10.1016/j.ijdrr.2019.101396.

[11] L. K. Comfort. “Crisis management in hindsight: Cognition, communication, coordination, and control”. In: *Public administration review* 67 (2007), pp. 189–197.

[12] A. Schmidt, J. Wolbers, J. Ferguson, and K. Boersma. “Are you Ready2Help? Conceptualizing the management of online and onsite volunteer convergence”. In: *Journal of Contingencies and Crisis Management* 26.3 (2018), pp. 338–349.

[13] V. Nespeca, T. Comes, and L. Alfonso. “Information Sharing and Coordination in Collaborative Flood Warning and Response Systems”. en. In: *ISD 2018 Conference Proceedings*. Aug. 2018.

[14] V. Nespeca, K. Meesters, and T. Comes. “Evaluating Platforms for Community Sensemaking: Using the Case of the Kenyan Elections”. In: *ISCRAM*. 2018.

[15] K. Meesters, V. Nespeca, and T. Comes. “Designing Disaster Information Management Systems 2.0: Connecting communities and responders.” In: *ISCRAM*. 2019.

[16] J. Wolbers and K. Boersma. “The common operational picture as collective sensemaking”. In: *Journal of Contingencies and Crisis management* 21.4 (2013), pp. 186–199.

[17] F. Mulder, J. Ferguson, P. Groenewegen, K. Boersma, and J. Wolbers. “Questioning Big Data: Crowdsourcing crisis data towards an inclusive humanitarian response”. In: *Big Data & Society* 3.2 (2016), p. 2053951716662054.

[18] N. Bharosa, M. Janssen, and Y.-H. Tan. “A research agenda for information quality assurance in public safety networks: information orchestration as the middle ground between hierarchical and netcentric approaches”. en. In: *Cognition, Technology & Work* 13.3 (Sept. 2011), pp. 203–216. issn: 1435-5566. doi: 10.1007/s10111-011-0172-9.

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[19] T. Comes. “Cognitive biases in humanitarian sensemaking and decision-making lessons from field research”. In: *2016 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*. Mar. 2016, pp. 56–62. doi: 10.1109/COGSIMA.2016.7497786.

[20] B. Van de Walle, B. Brugghemans, and T. Comes. “Improving situation awareness in crisis response teams: An experimental analysis of enriched information and centralized coordination”. In: *IJHCS* 95 (Nov. 2016), pp. 66–79. issn: 1071-5819. doi: 10.1016/j.ijhcs.2016.05.001.

[21] R. E. Morss, J. L. Demuth, H. Lazrus, L. Palen, C. M. Barton, C. A. Davis, C. Snyder, O. V. Wilhelmi, K. M. Anderson, D. A. Ahijevych, J. Anderson, M. Bica, K. R. Fossell, J. Henderson, M. Kogan, K. Stowe, and J. Watts. “Hazardous Weather Prediction and Communication in the Modern Information Environment”. In: *Bulletin of the American Meteorological Society* 98.12 (June 2017), pp. 2653–2674. issn: 0003-0007. doi: 10.1175/BAMS-D-16-0058.1.

[22] L. K. Comfort. “Self-Organization in Complex Systems”. In: *Journal of Public Administration Research and Theory: J-PART* 4.3 (1994), pp. 393–410. issn: 1053-1858.

[23] M. Turoff, M. Chumer, B. V. d. Walle, and X. Yao. “DERMIS: The Design of a Dynamic Emergency Response Management Information System”. English. In: *JITTA : Journal of Information Technology Theory and Application; Hong Kong* 5.4 (2004), pp. 1–35. issn: 15324516.

[24] W. N. Adger, T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockström. “Social-Ecological Resilience to Coastal Disasters”. en. In: *Science* 309.5737 (Aug. 2005). Publisher: American Association for the Advancement of Science Section: Special Viewpoints, pp. 1036–1039. issn: 0036-8075, 1095-9203. doi: 10.1126/science.1112122.

[25] F. H. Norris, S. P. Stevens, B. Pfefferbaum, K. F. Wyche, and R. L. Pfefferbaum. “Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness”. In: *American Journal of Community Psychology* 41.1-2 (Mar. 2008). Read, pp. 127–150. issn: 1573-2770. doi: 10.1007/s10464-007-9156-6.

[26] J. Rockström, A. V. Norström, N. Matthews, R. Biggs, C. Folke, A. Harikishun, S. Huq, N. Krishnan, L. Warszawski, and D. Nel. “Shaping a resilient future in response to COVID-19”. In: *Nature Sustainability* 6.8 (2023), pp. 897–907.

[27] B. Walker, C. S. Holling, S. R. Carpenter, and A. Kinzig. “Resilience, adaptability and transformability in social–ecological systems”. In: *Ecology and society* 9.2 (2004).

[28] C. Folke, S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. “Resilience thinking: integrating resilience, adaptability and transformability”. In: *Ecology and society* 15.4 (2010).

[29] T. Comes. “Designing for Networked Community Resilience”. In: *Procedia Engineering*. Humanitarian Technology: Science, Systems and Global Impact 2016, HumTech2016 159.Supplement C (Jan. 2016), pp. 6–11. issn: 1877-7058. doi: 10.1016/j.proeng.2016.08.057.

[30] R. M. Wise, I. Fazey, M. S. Smith, S. E. Park, H. C. Eakin, E. A. Van Garderen, and B. Campbell. “Reconceptualising adaptation to climate change as part of pathways of change and response”. In: *Global environmental change* 28 (2014), pp. 325–336.

[31] T. Comes, M. Warnier, W. Feil, and B. Van de Walle. “Critical airport infrastructure disaster resilience: A framework and simulation model for rapid adaptation”. In: *Journal of Management in Engineering* 36.5 (2020), p. 04020059.

[32] S. Krishnan, N. Y. Aydin, and T. Comes. “TIMEWISE: Temporal Dynamics for Urban Resilience-theoretical insights and empirical reflections from Amsterdam and Mumbai”. In: *npj Urban Sustainability* 4.1 (2024), p. 4.

[33] T. W. Malone, R. Laubacher, and C. Dellarocas. “The collective intelligence genome”. In: *MIT Sloan management review* (2010).

[34] T. W. Malone. *Superminds: The surprising power of people and computers thinking together*. Little, Brown Spark, 2018.

[35] M. Galesic, D. Barkoczi, A. M. Berdahl, D. Biro, G. Carbone, I. Giannoccaro, R. L. Goldstone, C. Gonzalez, A. Kandler, A. B. Kao, *et al.* "Beyond collective intelligence: Collective adaptation". In: *Journal of the Royal Society interface* 20.200 (2023), p. 20220736.

[36] G. Mulgan. *Big mind: How collective intelligence can change our world*. Princeton University Press, 2017.

[37] G. Mulgan. "Collective intelligence and governance: Imagining government as a shared brain". In: *The Routledge Handbook of Collective Intelligence for Democracy and Governance*. Routledge, pp. 70–77.

[38] K. Burnard and R. Bhamra. "Organisational resilience: development of a conceptual framework for organisational responses". In: *IJPR* 49.18 (2011), pp. 5581–5599.

[39] T. W. Malone and M. S. Bernstein. *Handbook of collective intelligence*. MIT press, 2022.

[40] J. W. Burton, E. Lopez-Lopez, S. Hechtlinger, Z. Rahwan, S. Aeschbach, M. A. Bakker, J. A. Becker, A. Berditchevskaia, J. Berger, L. Brinkmann, *et al.* "How large language models can reshape collective intelligence". In: *Nature Human Behaviour* (2024), pp. 1–13.

[41] L. Palen, K. M. Anderson, G. Mark, J. Martin, D. Sicker, M. Palmer, and D. Grunwald. "A Vision for Technology-mediated Support for Public Participation & Assistance in Mass Emergencies & Disasters". In: *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference*. ACM-BCS '10. Swinton, UK, UK: British Computer Society, 2010, 8:1–8:12. isbn: 978-1-4503-0192-3.

[42] A. S. Vivacqua and M. R. Borges. "Taking advantage of collective knowledge in emergency response systems". In: *Journal of Network and Computer Applications* 35.1 (2012), pp. 189–198.

[43] K. Starbird and L. Palen. "" Voluntweeters" self-organizing by digital volunteers in times of crisis". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2011, pp. 1071–1080.

[44] S. Vieweg, L. Palen, S. B. Liu, A. L. Hughes, and J. N. Sutton. *Collective intelligence in disaster: Examination of the phenomenon in the aftermath of the 2007 Virginia Tech shooting*. University of Colorado Boulder, CO, 2008.

[45] K. Starbird. "Delivering patients to sacré coeur: collective intelligence in digital volunteer communities". In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2013, pp. 801–810.

[46] M. Imran, C. Castillo, J. Lucas, P. Meier, and J. Rogstadius. "Coordinating human and machine intelligence to classify microblog communications in crises." In: *ISCRAM*. 2014.

[47] S. D. Ramchurn, T. D. Huynh, F. Wu, Y. Ikuno, J. Flann, L. Moreau, J. E. Fischer, W. Jiang, T. Rodden, E. Simpson, *et al.* "A disaster response system based on human-agent collectives". In: *Journal of Artificial Intelligence Research* 57 (2016), pp. 661–708.

[48] M. Vaccaro, A. Almaatouq, and T. Malone. "When combinations of humans and AI are useful: A systematic review and meta-analysis". In: *Nature Human Behaviour* (Oct. 2024). issn: 2397-3374. doi: 10.1038/s41562-024-02024-1.

[49] M. H. Tessler, M. A. Bakker, D. Jarrett, H. Sheahan, M. J. Chadwick, R. Koster, G. Evans, L. Campbell-Gillingham, T. Collins, D. C. Parkes, *et al.* "AI can help humans find common ground in democratic deliberation". In: *Science* 386.6719 (2024), eadq2852.

[50] M. Tsvetkova, T. Yasseri, N. Pescetelli, and T. Werner. "A new sociology of humans and machines". In: *Nature Human Behaviour* 8.10 (Oct. 2024), pp. 1864–1876. issn: 2397-3374. doi: 10.1038/s41562-024-02001-8.

[51] Y. Wang, M. McKee, A. Torbica, and D. Stuckler. "Systematic literature review on the spread of health-related misinformation on social media". In: *Social science & medicine* 240 (2019), p. 112552.

[52] S. Chen, L. Xiao, and A. Kumar. "Spread of misinformation on social media: What contributes to it and how to combat it". In: *Computers in Human Behavior* 141 (2023), p. 107643.

[53] N. Levina and E. Vaast. "The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems". In: *MIS quarterly* (2005), pp. 335–363.

[54] Y. Tim, S. L. Pan, P. Ractham, and L. Kaewkitipong. "Digitally enabled disaster response: the emergence of social media as boundary objects in a flooding disaster". In: *Information Systems Journal* 27.2 (2017), pp. 197–232.

[55] A. Sebastian, K. Lendering, B. Kothuis, A. Brand, S. Jonkman, P. Gelder, B. Kolen, M. Comes, S. Lhermitte, K. Meesters, B. van de Walle, A. Ebrahimi Fard, S. Cunningham, N. Khakzad, and V. Nespeca. *Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Tech. rep. Delft, South Holland, NL: TU Delft, Oct. 2017.

[56] S. E. Page. *The model thinker: What you need to know to make data work for you*. Basic Books, 2018.

[57] K. K. Stephens, J. L. Jahn, S. Fox, P. Charoensap-Kelly, R. Mitra, J. Sutton, E. D. Waters, B. Xie, and R. J. Meisenbach. "Collective sensemaking around COVID-19: Experiences, concerns, and agendas for our rapidly changing organizational lives". In: *Management communication quarterly* 34.3 (2020), pp. 426–457.

[58] J. Hernantes, E. Rich, A. Laugé, L. Labaka, and J. M. Sarriegi. "Learning before the storm: Modeling multiple stakeholder activities in support of crisis management, a practical case". In: *Technological Forecasting and Social Change* 80.9 (2013). Planning and Foresight Methodologies in Emergency Preparedness and Management, pp. 1742–1755. issn: 0040-1625. doi: https://doi.org/10.1016/j.techfore.2013.01.002.

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[59] M. Turoff, S. R. Hiltz, V. A. Bañuls, and G. Van Den Eede. "Multiple perspectives on planning for emergencies: An introduction to the special issue on planning and foresight for emergency preparedness and management". In: *Technological Forecasting and Social Change* 80.9 (2013). Planning and Foresight Methodologies in Emergency Preparedness and Management, pp. 1647–1656. issn: 0040-1625. doi: https://doi.org/10.1016/j.techfore.2013.07.014.

[60] S. Faraj and Y. Xiao. "Coordination in fast-response organizations". In: *Management science* 52.8 (2006), pp. 1155–1169.

[61] K. E. Weick. "Enacted sensemaking in crisis situations [1]". In: *Journal of management studies* 25.4 (1988), pp. 305–317.

[62] W. Muhren, G. V. D. Eede, and B. V. d. Walle. "Sensemaking and implications for information systems design: Findings from the Democratic Republic of Congo's ongoing crisis". In: *Information technology for development* 14.3 (2008), pp. 197–212.

[63] S. Maitlis and S. Sonenshein. "Sensemaking in crisis and change: Inspiration and insights from Weick (1988)". In: *Journal of management studies* 47.3 (2010), pp. 551–580.

[64] M. K. Christianson and M. A. Barton. "Sensemaking in the time of COVID-19". In: *Journal of management studies* 58.2 (2020), p. 572.

[65] E. A. Rouwette, J. A. Vennix, and A. J. Felling. "On evaluating the performance of problem structuring methods: an attempt at formulating a conceptual model". In: *Group Decision and Negotiation* 18.6 (2009), pp. 567–587.

[66] J. A. M. Vennix. *Group Model Building: Facilitating Team Learning Using System Dynamics*. en. Wiley, Aug. 1996. isbn: 978-0-471-95355-5.

[67] V. Nespeca, R. Quax, M. G. Rikkert, H. P. Korzilius, V. A. Marchau, S. Hadijsotiriou, T. Oreel, J. Coenen, H. Wertheim, A. Voinov, *et al.* "Towards participatory multi-modeling for policy support across domains and scales: a systematic procedure for integral multi-model design". In: *arXiv preprint* (Under review). url: https://doi.org/10.48550/arXiv.2402.06228.

SUMMARY

When disasters strike, local citizens often act as first responders, stepping in before public authorities or NGOs can provide assistance. This initial response gives rise to a disaster response system comprising a fluid network of organizations and groups, each taking on diverse roles and responsibilities. The disaster resilience of such systems, particularly their absorptive capacity, hinges on their ability to function as a cohesive collective. In other words, disaster response systems must demonstrate collective intelligence — i.e., the capacity to address complex problems in dynamic and evolving environments. This resilient and collectively intelligent behaviour depends on a combination of coordination and self-organization, a process referred to as *coordinated self-organization* in this dissertation. Central to this process is the exchange of timely and relevant information both within and across the groups operating in these disaster response systems.

Facilitating effective inter-group information exchange during disasters is, however, challenging due to their volatile nature. This volatility, marked by rapid and unpredictable environmental changes, prompts actors to adapt autonomously, resulting in self-organisation - i.e., the spontaneous emergence of new operational practices, such as new response groups and roles. These shifting roles lead to evolving information needs, making it difficult to identify who requires what and to deliver the right information to the right actors. The high volume of information generated by environmental volatility exacerbates this challenge, increasing the risk of information overload. As a result, information is often incomplete or unreliable, and even when available, its sheer volume impedes actors' ability to find and use the information they need.

Addressing the challenges of shifting information needs and information overload requires understanding and leveraging mechanisms that lead to the emergence of effective inter-group information exchange in volatile disaster response systems. Studying such mechanisms entails investigating how the micro-level behaviour of actors, together with its possible interplay with meso-level group characteristics and macro-level inter-group interactions and environmental factors (e.g., volatility), affects the emergence of effective inter-group information exchange in disasters. This approach to the study of inter-group disaster information sharing is termed Actor-Centred Disaster Information Sharing (ACDIS) in this thesis, with a particular focus on the implications of micro-level behaviour for inter-group information exchange. While a few studies have demonstrated the potential of this approach through case studies, Agent-Based Modelling (ABM), and disaster simulation exercises, a systematic approach to study disaster information sharing from an actor-centred perspective is missing. As such, the overarching

research question addressed by this thesis is: **How can actor-centred disaster information sharing that supports coordinated self-organisation be systematically analysed?**.

To answer this question, this thesis develops and demonstrates a methodology that combines ABM and case study research to study ACDIS across groups in a systematic manner. To this end, a research through design strategy is adopted, according to which the main design goal drives a series of design iterations producing design artifacts, insights, and directions for the following design iterations. The following research methods are used throughout these iterations: literature review, interviews and focus groups, content analysis, and modelling and simulation (ABM in particular).

This thesis addressed four critical knowledge gaps to enable the systematic study of ACDIS:

(1) An actor-centred conceptual framework that captures the key characteristics and requirements for disaster information sharing is missing. Such a framework is essential for systematically studying inter-group disaster information sharing through an actor-centred perspective.

(2) An ABM is missing to study inter-group disaster information sharing through an actor-centred perspective. This limits the ability to carry out research on the impact of micro-level behaviour of actors and its potential interplay with meso and macro level factors on the effectiveness of inter-group information exchange during disasters.

(3) A rigorous methodology is lacking for developing such an ABM through qualitative case study research. This methodology is required to balance the flexibility to capture the nuances of individual cases and phenomena of interest with the comparability needed to meaningfully compare findings across cases. The methodology is also required to ensure versatility in developing both empirical and theoretical models.

(4) The emergence of Informational Boundary Spanners (IBSs) as inter-group information exchange hubs in disaster contexts remains poorly understood, limiting the design of strategies for effective inter-group information sharing. Addressing this requires an actor-centred method to study IBS emergence and an ABM to simulate this process.

The following paragraphs illustrate how these gaps were addressed. To lay the foundation to address knowledge gaps (1)-(3), a methodology was developed for developing conceptual frameworks and ABMs through qualitative inquiry, focused on a phenomenon of interest, which in this case is ACDIS. This methodology is divided into two phases: framework development and model development. In the first phase, a conceptual framework is designed for the phenomenon of interest that captures its key characteristics and requirements. In the second phase, this framework is used in combination with a generic model to structure and interpret qualitative data and rigorously translate it into an ABM. This methodology was then applied to the case study of Jakarta, a critical case for studying ACDIS due to the frequent occurrence of floods and the significant number of organisations and community groups that need to coordinate while self-organizing in response to such floods.

To address knowledge gap (1), a conceptual framework was developed for ACDIS through the methodology based on the case study of Jakarta. A list of characteristics (and their attributes) were derived from a literature review of the fields of multi-actor systems, self-organisation, and information management. Then, these characteristics and attributes were used to design requirements for ACDIS. These requirements were validated and refined based on the case study of Jakarta. A conceptual framework was finally developed based on these requirements, thus filling knowledge gap (1).

To address knowledge gap (2), an ABM of ACDIS was developed through the methodology again based on the case study of Jakarta. The conceptual framework was used to analyse qualitative data from the case study to examine system configuration, self-organized change, and performance in terms of supporting co-ordinated self-organisation. The results from this analysis guided the development of an initial conceptual model (system identification and composition), which was subsequently refined and translated into a computational ABM. This translation involved structuring and interpreting the results of the analysis through the lens of the Generic Agent Model to derive agent rules. The outcome was an empirical model providing a non-reductionist description of ACDIS between the Marunda community in North Jakarta and other professional response organisations during the response to a flood. This model distinguished between information needs of which actors are unaware, defined as latent information needs, and those of which they are aware, termed known information needs. This distinction has implications for actors' information-sharing behaviour, as they cannot actively seek information if they are unaware of needing it (i.e., if their information needs are latent).

Simulation results with this model confirmed the initial case study finding that addressing latent information needs in a timely manner is particularly challenging and leads to greater information gaps compared to when needs are known. This finding is actor-centred, as it demonstrates how a micro-level factor - i.e., the presence of latent information needs and associated information-sharing behaviour — affects inter-group information sharing by reducing its effectiveness. These results demonstrated that the methodology enables the development of ABMs to study disaster information sharing by providing actor-centred insights in this field, thus addressing knowledge gap (2).

With regards to knowledge gap (3), the application of the methodology to the case of Jakarta illustrated that this methodology provides the means to maintain rigour in translating qualitative data into conceptual frameworks and ABMs for studying ACDIS. Further, the methodology balanced flexibility and comparability by prescribing to consistently apply the same conceptual framework across cases to maintain comparability, while enabling to choose generic models (and associated agent architectures) tailored to the specific case considered to ensure a degree of flexibility. Flexibility was also ensured by enabling to develop a conceptual framework for a phenomenon - i.e., ACDIS - for which such a framework was not available. Lastly, versatility was achieved by offering guidance for developing both theoretical and empirical models when studying the phenomenon of interest. These findings show that the proposed methodology addressed knowledge gap (3).

Concerning knowledge gap (4), A method was then developed to measure the emergence of Informational Boundary Spanners (IBSs) from an actor-centred perspective, focusing on the micro or individual level. Following this, a theoretical ABM was developed by abstracting from the previously developed ABM for the Jakarta case. A potential mechanism for the emergence of IBSs found through the Jakarta case was incorporated into this model, specifically the ability to learn which actors provide high-quality information. This mechanism was compared to a scenario where actors exchange information randomly without learning. The comparison was explored under varying conditions of environmental volatility, assessing the impact of learning in relation to different levels of information stability (uncertainty in information sources) and turbulence (the speed of environmental change).

The results of the simulation were then analysed using the actor-centred method for measuring the emergence of IBSs. The findings from this analysis show that, when learning occurs, this leads to the emergence of IBSs that are more effective in fostering inter-group information exchange compared to random information exchange. The emergence of effective IBSs through learning relies on stable information sources and a high level of connectivity across groups to effectively support inter-group information exchange and promote coordinated self-organisation and resilience at high levels of environmental volatility. These findings illustrate that the measurement method in combination with the ABM enabled to measure and understand the emergence of IBSs through an actor centred perspective, thus addressing knowledge gap (4).

In sum, this dissertation demonstrated how to systematically analyse disaster information sharing that supports coordinated self-organisation and resilience from an actor-centred perspective, thereby addressing the overarching research question posed in this thesis. It achieved this by developing and testing (a) a conceptual framework centred on the phenomenon of ACDIS, (b) two ABMs, that enabled the study of ACDIS, (c) a methodology for studying ACDIS through agent-based modelling and case study research (which enabled to develop the conceptual framework and the two ABMs), and (d) a method for measuring and understanding the emergence of IBSs from an actor-centred perspective based on ABM simulation results.

Implications for NGOs and public agencies aiming to foster resilience include, first, designing "smart" push-and-pull information-sharing strategies that account for latent information needs. Push notifications are effective for addressing latent information needs but can cause information overload if overused for both latent and known needs. To prevent this, "smart" push-and-pull strategies should use push notifications for latent needs and rely on on-demand (pull) sources for known needs. However, designing such strategies is non-trivial due to the inherent challenges of accurately identifying information needs and distinguishing between latent and non-latent categories. Second, fostering the exchange of relevant information across groups, thereby supporting coordinated self-organization, can be facilitated through the emergence of IBSs. This can be achieved in volatile environments by aggregating information about disruptions into a single, accessible source and by developing and maintaining numerous trusted connections between communities and professional response organizations.

This thesis demonstrated the potential synergies between collective intelligence and resilience in disaster response through coordinated self-organisation. It demonstrated how individual-level learning, particularly the ability of actors to identify high-quality information sources, fosters collective intelligence by enabling actors from different groups to identify and select effective IBSs who facilitate the exchange of relevant information across these groups. By promoting the exchange of high-quality information across groups, these effective IBSs support coordinated self-organization and enhance resilience's absorption capacity. The findings emphasize that collective intelligence, achieved through the identification and selection of effective IBSs, is crucial for strengthening absorption during disasters. However, addressing the persistent challenge of misinformation spread requires further research. Additionally, the synergies between collective intelligence capabilities — such as sensing, learning, and remembering — and resilience capacities — including absorption, adaptation, and transformation — remain insufficiently understood. To address these gap, this dissertation proposed an agenda on Collective Intelligence for Resilience, aimed at investigating these synergies in greater depth.

Samenvatting

Wanneer rampen toeslaan, treden lokale burgers vaak op als eerste hulpverleners voordat overheidsinstanties of ngo's hulp kunnen bieden. Deze eerste respons leidt tot een rampenresponssysteem dat bestaat uit een flexibel netwerk van organisaties en groepen, die elk verschillende rollen en verantwoordelijkheden op zich nemen. De rampbestendigheid van dergelijke systemen, met name hun absorptievermogen, hangt af van hun vermogen om als een samenhangend collectief te functioneren. Met andere woorden, rampenbestrijdingssystemen moeten blijk geven van collectieve intelligentie – ofwel het vermogen om complexe problemen aan te pakken in dynamische en veranderende omgevingen. Dit veerkrachtige en collectief intelligente gedrag is afhankelijk van een combinatie van coördinatie en zelforganisatie, een proces dat in dit proefschrift wordt aangeduid als "*gecoördineerde zelforganisatie*". Centraal in dit proces staat de uitwisseling van tijdige en relevante informatie, zowel binnen als tussen de groepen die in deze rampenbestrijdingssystemen opereren.

Het faciliteren van effectieve informatie-uitwisseling tussen groepen tijdens rampen is echter een uitdaging vanwege het vluchtige karakter ervan. Deze vluchtigheid, die wordt gekenmerkt door snelle en onvoorspelbare veranderingen in de omgeving, zet actoren ertoe aan zich autonoom aan te passen, wat resulteert in zelforganisatie - ofwel het spontane ontstaan van nieuwe operationele praktijken, zoals nieuwe responsgroepen en -rollen. Deze veranderende rollen leiden tot veranderende informatiebehoeften, waardoor het moeilijk wordt om te bepalen wie wat nodig heeft en om de juiste informatie aan de juiste actoren te leveren. De grote hoeveelheid informatie die wordt gegenereerd door de volatiliteit van het milieu verergert deze uitdaging, waardoor het risico op informatieoverbelasting toeneemt. Het gevolg is dat informatie vaak onvolledig of onbetrouwbaar is, en zelfs als deze beschikbaar is, belemmert de enorme hoeveelheid informatie de actoren in hun mogelijkheden om de informatie die ze nodig hebben te vinden en te gebruiken.

Om de uitdagingen van veranderende informatiebehoeften en informatieoverbelasting aan te pakken, moeten mechanismen die leiden tot het ontstaan van effectieve informatie-uitwisseling tussen groepen in onstabiele rampenbestrijdingssystemen worden begrepen en benut. Het bestuderen van dergelijke mechanismen houdt in dat onderzocht wordt hoe het gedrag van actoren op microniveau, samen met de mogelijke wisselwerking met groepskenmerken op mesoniveau en interacties tussen groepen op macroniveau en omgevingsfactoren (bijv. volatiliteit), van invloed is op het ontstaan van effectieve informatie-uitwisseling tussen groepen bij rampen. Deze benadering van de studie van informatie-uitwisseling tussen groepen bij rampen wordt in dit proefschrift Actor-Centred Disaster Information Sharing (ACDIS) genoemd, met een bijzondere focus op de implicaties van gedrag op microniveau voor informatie-uitwisseling tussen groepen. Hoewel enkele studies het potentieel van deze benadering hebben aangetoond door middel van casestudies, Agent-Based Modelling (ABM) en rampsimulatie-oefeningen, ontbreekt een systematische benadering om informatie-uitwisseling bij rampen te bestuderen vanuit een actor-gecentreerd perspectief. De overkoepelende onderzoeksvraag die in dit proefschrift aan de orde komt is dan ook: **Hoe kan actor-gecentreerde informatiedeling bij rampen die gecoördineerde zelforganisatie ondersteunt systematisch worden geanalyseerd?**

Om deze vraag te beantwoorden, wordt in dit proefschrift een methodologie ontwikkeld en gedemonstreerd die ABM en casestudy onderzoek combineert om ACDIS tussen groepen op een systematische manier te bestuderen. Daartoe wordt een ’research through design’-strategie toegepast, waarbij het belangrijkste ontwerpdoel een reeks ontwerpiteraties aanzet die artefacten, inzichten en aanwijzingen voor de volgende ontwerpiteraties opleveren. Tijdens deze iteraties worden de volgende onderzoeksmethoden gebruikt: literatuuronderzoek, interviews en focusgroepen, inhoudsanalyse en modellering en simulatie (met name ABM).

In deze dissertatie werden vier kritieke kennishiaten aangepakt om de systematische studie van ACDIS mogelijk te maken:

(1) Er ontbreekt een actorgericht conceptueel kader dat de belangrijkste kenmerken en vereisten voor rampeninformatiedeling vastlegt. Een dergelijk raamwerk is essentieel voor het systematisch bestuderen van rampeninformatiedeling tussen groepen door een actor-gecentreerd perspectief.

(2) Een ABM ontbreekt om inter-groep rampen informatiedeling te bestuderen vanuit een actor-gecentreerd perspectief. Dit beperkt de mogelijkheid om onderzoek te doen naar de impact van gedrag van actoren op microniveau en de mogelijke wisselwerking met factoren op meso- en macroniveau op de effectiviteit van informatie-uitwisseling tussen groepen tijdens rampen.

(3) Er ontbreekt een rigoureuze methodologie voor het ontwikkelen van een dergelijk ABM door middel van kwalitatief case study onderzoek. Deze methodologie is nodig om een evenwicht te vinden tussen de flexibiliteit om de nuances van individuele gevallen en fenomenen van belang vast te leggen en de vergelijkbaarheid die nodig is om bevindingen zinvol te vergelijken tussen verschillende gevallen. De methodologie is ook nodig om veelzijdigheid te garanderen bij het ontwikkelen van zowel empirische als theoretische modellen.

(4) De opkomst van Informational Boundary Spanners (IBSs) als knooppunten voor informatie-uitwisseling tussen groepen in rampencontexten blijft slecht begrepen, wat het ontwerp van strategieën voor effectieve informatie-uitwisseling tussen groepen beperkt. Om dit aan te pakken is een actor-gecentreerde methode nodig om de opkomst van IBS te bestuderen en een ABM om dit proces te simuleren.

De volgende paragrafen laten zien hoe deze lacunes zijn aangepakt. Om de basis te leggen voor het aanpakken van kennishiaten (1)-(3), werd een methodologie ontwikkeld voor het uitwerken van conceptuele raamwerken en ABM's door middel van kwalitatief onderzoek, gericht op ACDIS. Deze methodologie is verdeeld in twee fasen: ontwikkeling van een raamwerk en een model. In de eerste fase wordt een conceptueel raamwerk ontworpen voor het fenomeen waarin de belangrijkste kenmerken en vereisten worden vastgelegd. In de tweede fase wordt dit raamwerk gebruikt in combinatie met een generiek model om kwalitatieve gegevens te structureren en te interpreteren en rigoureus te vertalen naar een ABM. Deze methodologie werd vervolgens toegepast op de casestudy van Jakarta, een kritieke casus voor het bestuderen van ACDIS vanwege de frequente overstromingen en het aanzienlijke aantal organisaties en gemeenschapsgroepen die moeten coördineren en zichzelf moeten organiseren als reactie op dergelijke overstromingen.

Om kennishiaat (1) op te vullen, werd een conceptueel raamwerk ontwikkeld voor ACDIS door middel van de methodologie gebaseerd op de casestudie van Jakarta. Een lijst van kenmerken (en hun attributen) werd afgeleid uit een literatuuronderzoek op het gebied van multi-actor systemen, zelforganisatie en informatiebeheer. Vervolgens werden deze kenmerken en eigenschappen gebruikt om vereisten voor ACDIS te ontwerpen. Deze vereisten werden gevalideerd en verfijnd op basis van de casestudie van Jakarta. Uiteindelijk werd een conceptueel raamwerk ontwikkeld op basis van deze vereisten, waarmee kennishiaat (1) werd opgevuld.

Om kennishiaat (2) aan te pakken, werd een ABM van ACDIS ontwikkeld via de methodologie, opnieuw gebaseerd op de casestudie van Jakarta. Het conceptuele raamwerk werd gebruikt om kwalitatieve gegevens van de casestudy te analyseren om de systeemconfiguratie, zelfgeorganiseerde verandering en prestaties te onderzoeken in termen van ondersteuning van gecoördineerde zelforganisatie. De resultaten van deze analyse gaven richting aan de ontwikkeling van een eerste conceptueel model (systeemidentificatie en -samenstelling), dat vervolgens werd verfijnd en vertaald naar een computationeel ABM. Deze vertaling bestond uit het structureren en interpreteren van de resultaten van de analyse door de lens van het Generic Agent Model om agentregels af te leiden. Het resultaat was een empirisch model dat een niet-reductionistische beschrijving geeft van ACDIS tussen de Marunda-gemeenschap in Noord-Jakarta en andere professionele hulpverleningsorganisaties tijdens de respons op een overstroming. Dit model maakte onderscheid tussen informatiebehoeften waarvan actoren zich niet bewust zijn, gedefinieerd als latente informatiebehoeften, en informatiebehoeften waarvan ze zich wel bewust zijn, aangeduid als bekende informatiebehoeften. Dit onderscheid heeft gevolgen voor het informatie-uitwisselingsgedrag van actoren, omdat ze niet actief op zoek kunnen gaan naar informatie als ze niet weten dat ze die nodig hebben (ofwel als hun informatiebehoeften latent zijn).

Simulatieresultaten met dit model bevestigden de eerste casestudiebevinding dat het tijdig aanpakken van latente informatiebehoeften bijzonder lastig is en leidt tot grotere informatielacunes in vergelijking met wanneer de behoeften bekend zijn. Deze bevinding is gericht op actoren, omdat het aantoont hoe een factor op microniveau - ofwel de aanwezigheid van latente informatiebehoeften en het bijbehorende informatie-uitwisselingsgedrag - de informatie-uitwisseling tussen groepen beïnvloedt door de effectiviteit ervan te verminderen. Deze bevindingen tonen aan dat de methodologie de ontwikkeling van ABM's voor het bestuderen van informatiedeling bij rampen mogelijk maakt door actor gecentreerde inzichten op dit gebied te bieden, waarmee kennishiaat (2) wordt aangepakt.

Met betrekking tot kennishiaat (3) liet de toepassing van de methodologie op de casus Jakarta zien dat deze methodologie de middelen biedt om striktheid te handhaven bij het vertalen van kwalitatieve gegevens naar conceptuele raamwerken en ABMs voor het bestuderen van ACDIS. Verder bracht de methodologie flexibiliteit en vergelijkbaarheid in balans door consequent hetzelfde conceptuele raamwerk toe te passen in verschillende casussen. Daarmee blijft de vergelijkbaarheid behouden, terwijl het tevens mogelijk is om generieke modellen (en bijbehorende agentarchitecturen) te kiezen afgestemd op de specifieke casus om een zekere mate van flexibiliteit te waarborgen. Flexibiliteit werd ook gewaarborgd door het mogelijk te maken een conceptueel raamwerk te ontwikkelen voor een fenomeen – ofwel actor-gecentreerde informatiedeling bij rampen - waarvoor een dergelijk raamwerk niet beschikbaar was. Tot slot werd veelzijdigheid bereikt door richtlijnen te bieden voor het ontwikkelen van zowel theoretische als empirische modellen bij het bestuderen van het fenomeen van belang. Deze bevindingen tonen aan dat de voorgestelde methodologie kennishiaat (3) heeft aangepakt.

Met betrekking tot kennishiaat (4) werd vervolgens een methode ontwikkeld om de opkomst van Informational Boundary Spanners (IBSs) te meten vanuit een actor-gecentreerd perspectief, gericht op het micro- of individuele niveau. Vervolgens werd een theoretisch ABM ontwikkeld door te abstraheren van het eerder ontwikkelde ABM voor de Jakarta-casus. Een potentieel mechanisme voor het ontstaan van IBS'en dat werd gevonden in de Jakarta-casus werd opgenomen in dit model, met name de mogelijkheid om te leren welke actoren informatie van hoge kwaliteit leveren. Dit mechanisme werd vergeleken met een scenario waarin actoren willekeurig informatie uitwisselen zonder te leren. De vergelijking werd onderzocht onder verschillende omstandigheden van volatiliteit, waarbij het effect van leren werd beoordeeld in relatie tot verschillende niveaus van informatiestabiliteit (onzekerheid in informatiebronnen) en turbulentie (de snelheid van milieuverandering).

De resultaten van de simulatie werden vervolgens geanalyseerd met behulp van de actor-gecentreerde methode voor het meten van de opkomst van IBSs. De bevindingen van deze analyse laten zien dat, wanneer leren optreedt, dit leidt tot het ontstaan van IBS'en die effectiever zijn in het bevorderen van informatie-uitwisseling tussen groepen in vergelijking met willekeurige informatie-uitwisseling. Het ontstaan van effectieve IBSs door leren is afhankelijk van stabiele informatiebronnen en een hoog niveau van connectiviteit tussen groepen om de uitwisseling van informatie tussen groepen effectief te ondersteunen en gecoördineerde zelforganisatie en veerkracht te bevorderen bij hoge niveaus van volatiliteit van de omgeving. Deze bevindingen illustreren dat de meetmethode in combinatie met het ABM het mogelijk maakte om het ontstaan van IBS'en te meten en te begrijpen vanuit een actor-gecentreerd perspectief, en zo de kennishiaat (4) te dichten.

Samengevat laat dit proefschrift zien hoe informatie-uitwisseling bij rampen, die gecoördineerde zelforganisatie en veerkracht ondersteunt, systematisch kan worden onderzocht en geanalyseerd vanuit een actor-gecentreerd perspectief, waarmee de overkoepelende onderzoeksvraag van dit proefschrift werd beantwoord. Dit werd bereikt door het ontwikkelen en testen van (a) een conceptueel raamwerk gericht op het fenomeen ACDIS, (b) twee ABMs, die de studie van ACDIS mogelijk maakten, (c) een methodologie voor het bestuderen van ACDIS door middel van agent-based modelling en case study onderzoek (die het mogelijk maakte om het conceptuele raamwerk en de twee ABM's te ontwikkelen), en (d) een methode voor het meten en begrijpen van de opkomst van IBSs vanuit een actor-gecentreerd perspectief gebaseerd op ABM simulatieresultaten.

Implicaties voor NGO's en overheidsinstanties die veerkracht willen bevorderen zijn, ten eerste, het ontwerpen van "slimme" push-and-pull strategieën voor het delen van informatie die rekening houden met latente informatiebehoeften. Pushberichten zijn effectief om te voorzien in latente informatiebehoeften, maar kunnen een overload aan informatie veroorzaken als ze te veel worden gebruikt voor zowel latente als bekende behoeften. Om dit te voorkomen zouden "slimme" push-and-pull strategieën pushberichten moeten gebruiken voor latente behoeften en moeten vertrouwen op bronnen op aanvraag (pull) voor bekende behoeften. Het ontwerpen van dergelijke strategieën is echter niet-triviaal vanwege de inherente uitdagingen om informatiebehoeften nauwkeurig te identificeren en onderscheid te maken tussen latente en niet-latente categorieën. Ten tweede kan het bevorderen van de uitwisseling van relevante informatie tussen groepen, waardoor gecoördineerde zelforganisatie wordt ondersteund, worden vergemakkelijkt door het ontstaan van IBS'en. Dit kan worden bereikt in instabiele omgevingen door informatie over rampen samen te brengen in één enkele, toegankelijke bron en door het ontwikkelen en onderhouden van talrijke betrouwbare verbindingen tussen gemeenschappen en professionele responsorganisaties.

Deze dissertatie toont de potentiële synergie aan tussen collectieve intelligentie en veerkracht bij rampenbestrijding door middel van gecoördineerde zelforganisatie. Het laat zien hoe leren op individueel niveau, met name het vermogen van actoren om informatiebronnen van hoge kwaliteit te identificeren, collectieve intelligentie bevordert door actoren uit verschillende groepen in staat te stellen om effectieve IBS'en te identificeren en te selecteren die de uitwisseling van relevante informatie tussen deze groepen vergemakkelijken. Door de uitwisseling van hoogwaardige informatie tussen groepen te bevorderen, ondersteunen deze effectieve IBS'en gecoördineerde zelforganisatie en vergroten ze het absorptievermogen van veerkracht. De bevindingen benadrukken dat collectieve intelligentie, bereikt door de identificatie en selectie van effectieve IBS'en, cruciaal is voor het versterken van absorptie tijdens rampen. Om het hardnekkige probleem van de verspreiding van verkeerde informatie aan te pakken, is echter verder onderzoek nodig. Bovendien is er nog onvoldoende inzicht in de synergie tussen collectieve intelligentiecapaciteiten - zoals waarnemen, leren en onthouden - en veerkrachtcapaciteiten - waaronder absorptie, aanpassing en transformatie. Om deze lacunes aan te pakken, komt dit proefschrift tot een agenda voor Collectieve Intelligentie voor Veerkracht, gericht op het diepgaander onderzoeken van deze synergiën.

Appendix A: Generic Agent Model (GAM)

This appendix provides a brief description of the Generic Agent Model designed by Brazier et al. [1] based on the weak notion of agent introduced by Wooldridge et al. [2, 3]. This appendix focuses specifically on GAM's process composition. Further details including the generic model's knowledge composition can be found in [1]. A generic model's process composition includes the models' task hierarchy (abstracted tasks and their sub-tasks), tasks' inputs and outputs, tasks' information exchange (executed through information links among tasks), and task control knowledge (capturing the sequencing of tasks).

1. Process Composition

1.1. Task hierarchy

The task hierarchy of GAM includes only two hierarchical levels, namely that of the agent and the abstracted tasks (or components) carried out by the agent. Such abstracted tasks are the Own Process Control (OPC), Agent Interaction Management (AIM), World Interaction Management (WIM), Maintenance of Agent Information (MAI), Maintenance of World Information (MWI), and Agent Specific Tasks (AST) (see figure 1).

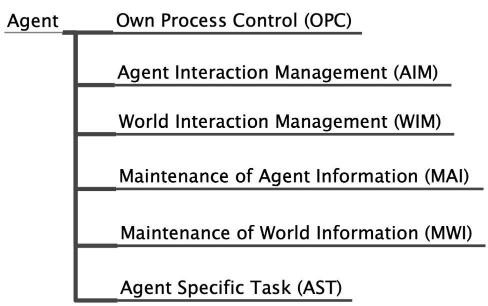

Figure 1: Task hierarchy of the Generic Agent Model (GAM).

The OPC component maintains a self-model of the agent (i.e. a model of the agents' goals and, in general, of the characteristics that distinguish them), and carries out decisions to trigger further tasks that are performed by other components of GAM. The AIM component executes interactions with other agents such as receiving or sharing information e.g. when requested to do so by the OPC. The WIM component carries out interactions with the environment or world such as performing observations of the environment. The MAI component maintains information regarding other agents that the agent may use to carry out other tasks (such as deciding who to cooperate with, Cf. [4]) and provides this information to other tasks when requested to do so. The MWI task stores information from the environment (e.g. shocks and announcements) that the agent finds relevant and provide it to other tasks or agents when this information is requested by other tasks. Finally, the AST task is associated with domain-specific tasks an agent carries out such as combining different pieces of information to obtain new information [4].

1.2. Task input and output

The tasks' inputs and outputs for GAM are shown in table 1.

Task (or process)	**Input information types**	**Output information types**
own process control	belief info	own characteristics
agent interaction management	incoming communication info, own characteristics, belief info	outgoing communication info, maintenance info
world interaction management	observation result info, own characteristics, belief info	observation info, action info, maintenance info
maintenance of agent information	agent info	agent info
maintenance of world information	world info	world info

Table 1: GAM's input and output information types, from [1].

1.3. Information exchange

The information exchange among tasks is defined by information links among tasks that enable the exchange of information. Figure 2 shows the tasks included in GAM (according to the task hierarchy) and their information links used for information exchange.

1.4. Task control knowledge

Task control knowledge defines the conditions under which particular tasks are carried out, and the goals or targets associated with the activation of tasks. In practice, such a knowledge is represented as a set of rules capturing the triggering knowledge states (or activation conditions) under which a task is executed, the task that is executed, the target (or goal) that determines when the task is concluded, and possibly other statements capturing e,g. the activation of information sharing links that enable to share information among tasks. Triggering knowledge states can e.g. be associated with the activation of a parent task or agent, or the availability of new input information through an information link that provides input to the considered task. The following pseudo code shows the general structure of task control knowledge.

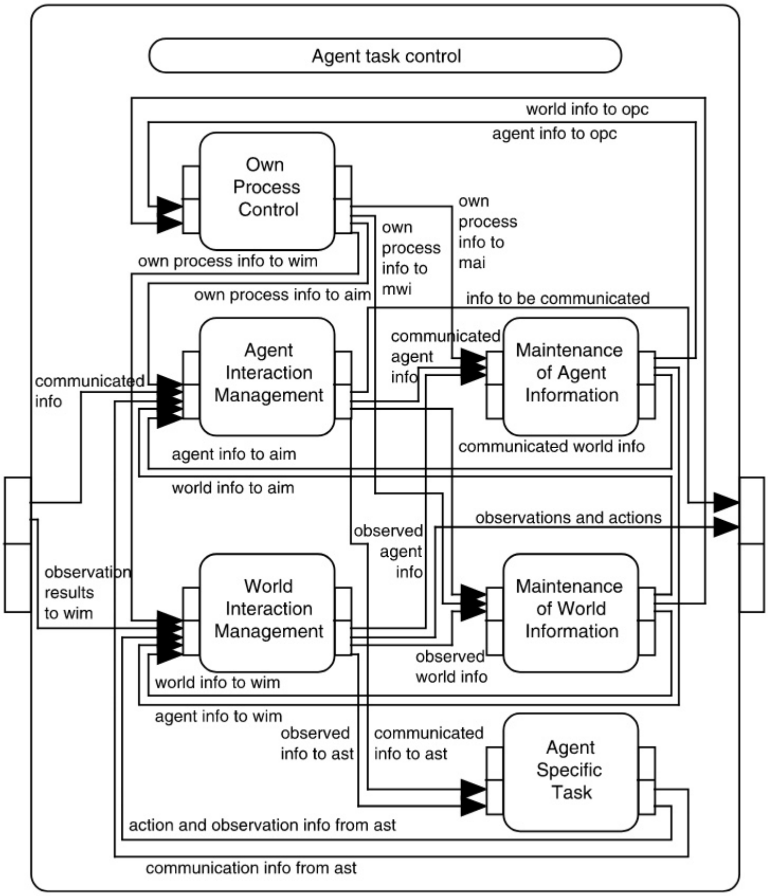

Figure 2: Information exchange among GAM's tasks [1].

```
if activation_condition
then next_component_state(task_to_execute_name, active)
and next_target_set(target_name)
```

In the case of GAM, only the agent has sub-tasks (e.g. OPC, AIM, etc.). All of these tasks are primitive, meaning they do not have sub-tasks. As such, the task control knowledge included in GAM only pertains to the agent (represented as "Agent task control" in figure 2). GAM's task control knowledge dictates that all tasks and information links are activated at the beginning of the simulation. This means in practice that all tasks process incoming information as soon as it is received as an input by the task (in an asynchronous manner). The following pseudo code shows the task control knowledge for two tasks and one information sharing link among them all of which are included in GAM (Cf. figure 2). Task control knowledge for the remaining tasks and links (shown in figure 2) is specified according the same structure as that shown in the example below.

```
if start
then next_component_state(own_process_control, awake)

if start
then next_component_state(agent_interaction_management, awake)

if start
then next_link_state(own_process_info_to_wim, awake)
```

REFERENCES

[1] F. M. Brazier, C. M. Jonker, and J. Treur. “Compositional design and reuse of a generic agent model”. In: *Applied Artificial Intelligence* 14.5 (2000), pp. 491–538.

[2] M. Wooldridge and N. R. Jennings. “Agent theories, architectures, and languages: a survey”. In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1994, pp. 1–39.

[3] M. Wooldridge and N. R. Jennings. “Intelligent agents: Theory and practice”. In: *The knowledge engineering review* 10.2 (1995), pp. 115–152.

[4] F. M. Brazier, C. M. Jonker, and J. Treur. “Formalisation of a cooperation model based on joint intentions”. In: *International Workshop on Agent Theories, Architectures, and Languages*. Springer. 1996, pp. 141–155.

Appendix B: Overview, Design Concepts and Details of the descriptive ABM

1. Purpose

This model is intended to study how the way information is collectively managed (i.e. shared, collected, processed, and stored) in a system performs during a crisis or disaster. Performance is assessed in terms of the system's ability to provide the information needed to the actors who need it when they need it. There are two main types of actors in the simulation, namely communities and professional responders. Their ability to exchange information is crucial to improve the system's performance as each of them has direct access to only part of the information they need.

This model has a descriptive purpose [1]. Specifically, the purpose is to capture knowledge regarding disaster information management from literature, previously existing models and case study research. The considered case or system is the Marunda community of north-east Jakarta and other professional responders that may exchange information with the community. The community and professional responders have to respond to a disaster (a flood).

2. Entities, Properties, States, and Tasks

Figure 1 shows the entities considered in the model, their properties as in the constant characteristics that describe them, the state variables as in the variables that capture the current state of an entity, and the tasks (or methods) these entities carry out.

2.1. Types of Actors: Communities and Professionals

There are two main types of actors in the simulation: communities and professional responders.

Communities are placed in the disaster-struck area on right side of the modelled world (see figure 2). Such area is divided administratively in RTs (neighbourhood units), RWs (community units, made of RTs), and the administrative village (made of RWs). The considered disaster affected area does not include the whole administrative village of Marunda, but only only 3 of its RWs: 7,10 and 11. Community

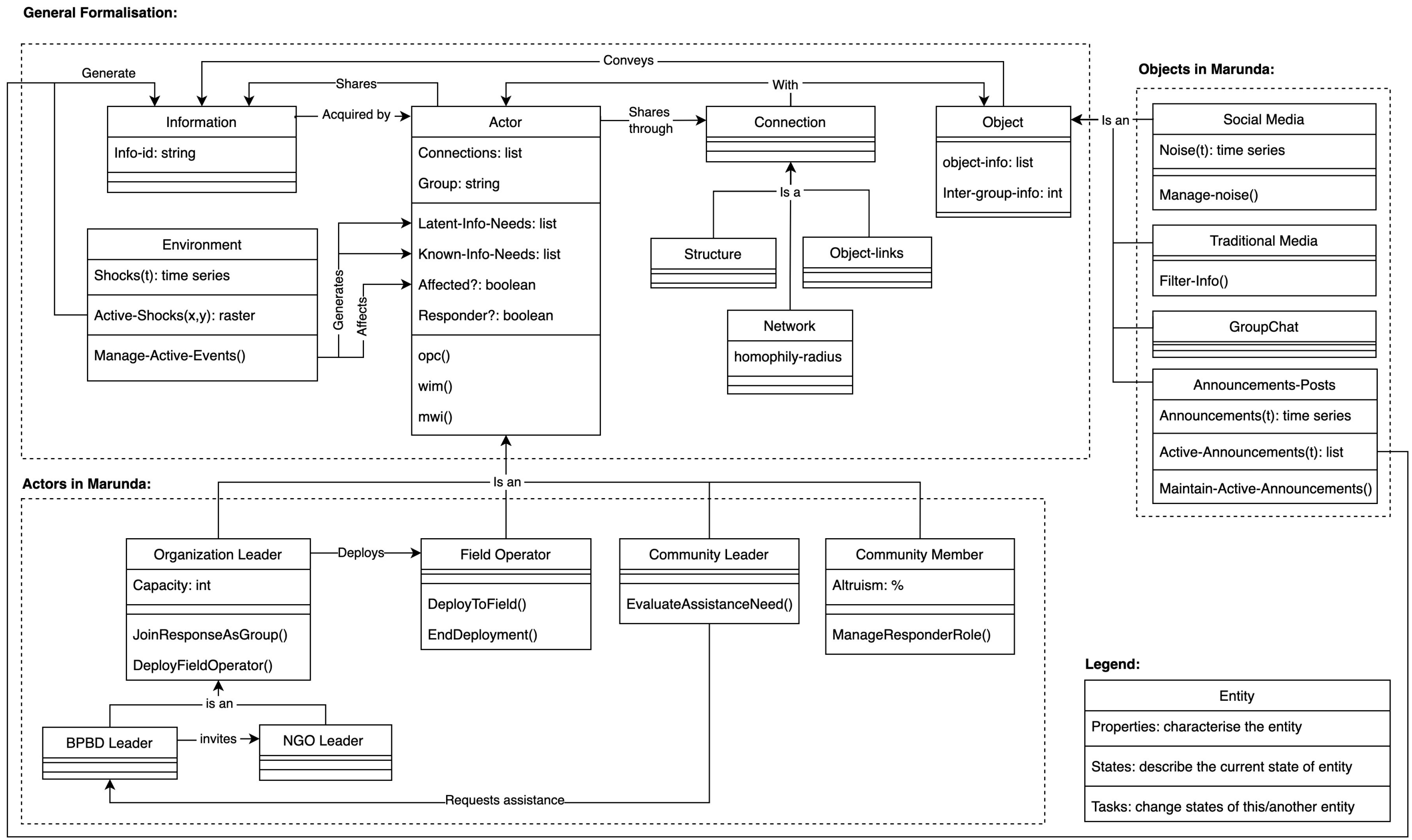

Figure 1: Description of entities, their properties, states and tasks in disaster Information Management (IM) both in general and for the case study of Marunda.

members are hierarchically organized from bottom to top of the hierarchy in community members, RT leaders, RW leaders and the village leader (figure 1 summarizes the last three as "community leader" for simplicity).

Professionals responders are placed on the left side of the world (see figure 2). They are divided in different groups: the BPBD (provincial disaster management organisation of the Jakarta Greater Area) and NGOs that participate in the response to floods (e.g. the Red Cross). Each of these groups is divided hierarchically in field operators, tactical operators, and the leader. Field operators can be deployed (transferred) to the disaster affected area to help.

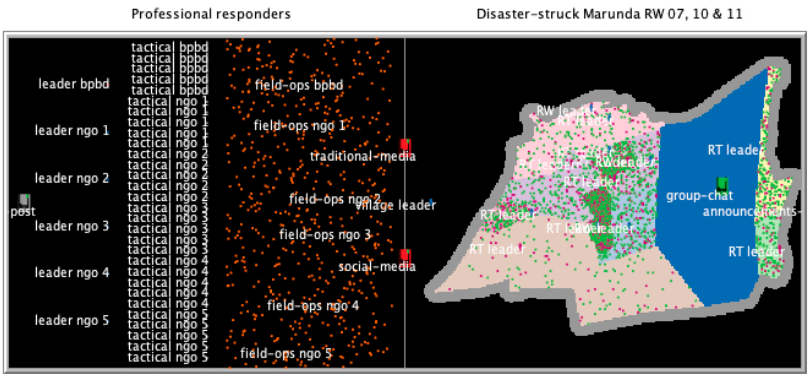

Figure 2: Modelled world. The blue area to the right corresponds to a flood diversion canal and the adjacent uninhabited area.

2.2. Types of Events: Shocks and Announcements

There are two types of events: shocks and announcements. Shocks occur within the considered disaster affected area (right side of the world cf. Figure 2). They represent the cascading consequences of the initial occurrence of a disaster. All responding actors (both communities and professionals) need to find out about shocks. As shocks occur within the disaster affected area, they are easier to find for communities (and field operators when deployed to the disaster-struck area) than for the professional responders who are not physically there.

Announcements represent the pieces of information that are relevant for all actors in the simulation but cannot be found in the disaster affected area. Examples of announcements could be a flood warning, or an update of an incoming hurricane. Announcements are more readily available for professional responders than for communities. Specifically, they can be accessed through the announcements-post object by all professional responders (in the left side of the world see Figure 2) while communities can only receive this information when it is shared by professional responders.

2.3. Types of Information Needs: Latent and Known

There are two types of information needs: latent and known. Latent (or unknown) information needs are those that the actors are not aware of. As such, the actors cannot actively look for the information they need. Conversely, known information needs are those the actors are aware of and can therefore actively look for the related information. In the simulation, each event (shock or announcement) comes with updates. The event itself is associated with one unknown information need. Conversely, the updates on the event constitute (potentially) known information needs as the actors can become aware of the event, but can expect that follow-up updates will be available.

2.4. Objects

Objects are introduced in the model to represent all non-actor entities that contribute to the exchange of information. Actors can access an object when they have an object-link to it. When pressing the "make-links" button the object-links are shown in grey in the model interface. Four objects are introduced in the model, as in the following.

- The traditional media object is used to represent the role of the press. Only professionals can post to the object but everybody can access it. Information posted to the traditional media object is filtered of (a) information associated with events that are no longer active and (b) irrelevant information (also called noise). The release of the posted information is delayed under the assumption that verifying information takes time.
- The social media object represents the role of social media platforms such as Facebook and Instagram. Everyone can post to and access information from this object. External noise is injected in the social media object regularly to simulate irrelevant information incoming from outside the system.
- The announcement posts object represents sources of information from outside the system that are relevant for the actors in the system.
- The group chat object represents a WhatsApp group that the community uses to exchange information during floods.

2.5. Irrelevant Information: Noise

Noise represents information that is irrelevant for all the actors. The presence of such information can contribute to overwhelm the actors with information, thus possibly affecting their ability find and exchange the information needed. Two types of noise are included in the model:

- Internal noise: the irrelevant information shared by the agents in the simulation to other agents and objects.

- External-noise: irrelevant information being injected in the system from the outside world. Such external noise it regularly injected (or posted) within the social media object.

3. Scales

The model adopts the following temporal and spatial scales.

Regarding the temporal dimension, one tick or time interval of simulation corresponds to 10 minutes in the real world. This time step was chosen to capture to volatility and extreme variability of disaster response, in which new disruptive events may occur and new information may become available very often. The duration of the simulation is set in days and can be defined by the user. This is because the duration of a flood in Marunda can span one or more days.

In terms of spatial dimensions, the geospatial area of the considered disaster struck area is of 7.92 Km^2 and it is divided in a total of 19991 patches. As such, 1 patch corresponds to an area of 396 m^2 and a diagonal of 28 m. This scale is important when setting parameters such as agent vision and shock areal influence.

4. Process overview and Scheduling

In a nutshell, the following occurs during a simulation. Due to a disaster, a series of randomly occurring disruptive events takes place. The actors in the simulation need to keep track of such events. Specifically, each event generates information needs for the different actors, which increases the information gaps (i.e. the "piles" of unaddressed information needs). In order to reduce the information gaps, the actors need to "discover" the pieces of information they need. The desired behaviour or performance of the system is to keep the information gaps as low as possible, which is to address as many information needs as possible as they occur. The processes and their scheduling is shown at an aggregate level in the following:

1. Manage events & needs: releases disruptive events (shocks and announcements) and adds the associated information needs for the actors that would find that particular event relevant.

2. Manage Objects: release delayed and filtered information that was previously shared to the traditional media object by professional responders.

3. Manage Actors' Activities: decides upon (a) the actors' information management activities (collecting, processing, and sharing), (b) whether community members decide to become responders, and (c) requests or provision of assistance across communities and professional responders.

4. Manage Noise: releases external noise in the social media object.

5. Compute output variables: calculates Relevance and Timeliness gaps in total, for latent and known needs, and for communities and professionals.

5. Design Concepts

5.1. Emergence

The model was designed to study the emergence of patterns in the relevance and timeliness information gaps when two loosely connected groups, namely professional responders and communities, need to share information to address their information needs in the response to a disaster. These patterns are emergent as they result from the individual actions of autonomous agents representing actors, given their connections to other agents and the occurrence of disruptive events. Adaptation and fitness are not considered in this model.

5.2. Sensing

When looking for information in proximity, the actors in the disaster-struck area can sense when there are active shocks or other actors in the surroundings. Further, when affected by a given shock, the actors can sense it and share such information. Finally, when processing information ("receive info" in figure 1), the actors become aware when they find information that addresses their information needs and/or that may address the needs of others.

5.3. Interactions

Actors interact by sharing and collecting information from other actors and from the environment. Specifically, an actor can share and collect information in the following ways.

- In proximity: if the actor is placed in the disaster struck area (see figure 2) it can share or collect information in proximity. Specifically the actor can collect from the surrounding environment or by having an in-person meeting with other actors within the "agent-vision" radius.
- In remote: the actor can share or collect information from the other actors and objects the actor has connections with.

5.4. Stochasticity

The altruism parameter was considered as a probability and was extracted from a uniform probability distribution. This is to account for the diversity that different actors can have in the community (or "demographic noise" [2]).

Stochasticity was also included in the setup of the social networks within and across communities and professional responders. This is to consider the uncertainty deriving from the fact that social networks were not deduced from data.

Further, stochasticity was used to determine the outcomes of the activities carried out by the actor during the simulation. For instance, the actors randomly choose which other agents to collect and share information from/to. This is a deliberate simplification. It is assumed that the actors do not prioritize particular sources or recipients of their information based on who or what they are. However, the preferences of the actors are still to some extent accounted for as the actors can only share information in remote through their previously existing connections (structures, networks, and object links).

5.5. Collectives

The actors are grouped in two main collectives: communities and professional responders. The model is engineered so that - to keep information gaps low - the actors within the system need to exchange information about shocks and announcements across the boundaries of these two collectives (cf. Section 2.2). Effectively sharing information across this two collectives is indeed a recognized challenge in disaster management.

5.6. Observations: Information Gaps

The performance of the system is measured in terms of the information gaps. The lower the information gaps are kept along the simulation, the higher the performance of the system will be.

There are two types of information gaps: relevance and timeliness gaps. Information relevance is associated with addressing information needs of the actors without any time limitation. Information timeliness is associated with addressing information needs before it is too late to act upon that information. To account for timeliness, the information needs in the model are assigned an expiration time. As such, timely information is that which is received by the actors before the expiration of the associated information needs. When an information need expires it can no longer be addressed on time and thus it cannot reduce the timeliness gap. However, this information can still address the information need and reduce the relevance gap. As such, the timeliness gap is always equal or higher than the relevance gap.

6. Model Initialization

When pressing the button "Setup" the model is initialized with the input data and parameters of choice according to the following procedure.

1. The world is setup according to the geospatial data provided as input (see Section 7).

2. The agents representing the actors are set and positioned on the map also according to the geospatial data.

3. The objects are created and, the actor’s access to such objects is set through object links.

4. The Networks of each actor in the disaster-affected area is setup considering preferential attachment, triadic closure, and proximity as a proxy for homophily (resulting in scale free networks).

5. The Structures are setup according to the predefined and hierarchical arrangements for information sharing.
6. The events are setup as lists containing their time of occurrence, duration and the associated updates.
7. The external noise is setup as a list containing the number of noise instances to be introduced at each time step.
8. The global variables used to calculate information gaps as set to 0.

The lists describing events and noise are set to be always the same given the same set of parameters (i.e. they are set with the same random seed). This is to ensure comparability across different simulations.

7. Model Input

The input data is geospatial information (shapefiles) on the administrative boundaries of RWs 07, 10 and 11 and of the associated RTs in the Marunda community. Such information is used to setup the world and it division in disaster struck area and area of the professional responders.

The shapefiles also include information on the number of inhabitants of age above 13 years old within each boundary. This information is used to create as many community members within each RW and RT administrative boundary during the model initialization.

8. Sub-models

8.1. Manage Events & Needs

This sub-model includes the following steps:

1. check if there are new events and set them as active.
2. Add latent information needs associated with new events to the actors for which the events are relevant. Shocks are relevant for all professional responders. Shocks are also relevant for community members who decide to become responders (see next section). Announcements are relevant for everyone in the simulation.
3. Update event duration. If the duration of any of the currently active events is over, set them as inactive and remove them from the system. In the case of shocks, actors become no longer responding to or affected by the shocks that became inactive.
4. If there are any active events, check if there is an update to be released.
5. Add known information needs associated with the new update to the actors for which the update on the event is relevant (same as for latent information needs).

8.2. Manage Actors' Activities

This sub-model includes the following steps:

1. Randomly choose whether to process the received info or collect new info.
    a) Processing received info: evaluates if the information addresses any of the actor's information needs
    b) Collecting new info: If the actor does not have any known information needs it can check the surrounding environment and possibly find shocks (if in the disaster affected area). Else, if the actor has known information needs, it randomly picks whether to collect from actors in proximity, from the surrounding environment, from actors in its network, or from one of the objects it has access to.
2. Become responder: Check if community members who become aware of a shock while collecting or processing received info decide to become responders based on their altruism.
3. Share information:
    a) If any relevant information was found the actors share it to one of the following (randomly chosen): nearby actors, actors in their networks, or objects to which they are linked.
    b) If no relevant information was found, the actors share irrelevant information (internal noise).
4. Request and Send Assistance (more in the following section).

8.3. Request and Send Assistance

Community members request for assistance via their community leaders to the government, who then deploys field operators and ask other NGOs to contribute. This process is simulated as in the following.

1. Communities request help:
    a) It is assumed that the RW leader will share a request for assistance when it finds that too many shocks and announcements are occurred since the beginning of the simulation (more than 10). When this threshold is passed, the RW leader requests help to the village leader.
    b) The village leader takes an hour to make a decision and then requests assistance to the leader of the provincial disaster management organisation BPBD.
2. Professional responders provide help:
    a) the leader of BPBD takes an hour to decide. Then, it joins the response on behalf of its group and deploys (transfers) a number of field operators to the disaster affected area (from the left to the right side of the world, cf. Figure 2).

b) The professional responder that have been deployed take an hour to reach the disaster affected area.

c) The leader of BPBD can also ask other NGOs to join the response and deploy their field operators.

8.4. Compute Information Gaps

The relevance and timeliness gaps are calculated as in the following.

$$Relevance\ Gap\ (t) = \frac{\sum_{k=1}^{n_{actors}} (info\ needs\ _k\ (t) - info\ needs\ addressed\ _k\ (t))}{n_{actors}} \quad (1)$$

$$Timeliness\ Gap\ (t) = \frac{\sum_{k=1}^{n_{actors}} (info\ needs\ _k\ (t) - info\ needs\ addressed\ on\ time\ _k\ (t))}{n_{actors}} \quad (2)$$

Where:

- n_{actors} = total number of actors in the simulation;
- $info\ needs\ _k\ (t)$ = total information needs received by the actor k at the simulation time (t).
- $info\ needs\ addressed\ _k\ (t)$ = total information needs addressed for the actor k at the simulation time (t)
- $info\ needs\ addressed\ on\ time\ _k\ (t)$ = total information needs addressed before their expiration for the actor k at the simulation time (t)

The last three variables are globals that are updated at key points in the model narrative i.e. when new information needs are added to an actor as a consequence of the occurrence of a new event and when the actors finds information that addresses their needs.

9. Source code and data

The model code and input data can be found on the CoMSES computational model library by searching for "*Share: bottom-up disaster information management*" (or click the link here).

REFERENCES

[1] B. Edmonds, C. Le Page, M. Bithell, E. Chattoe-Brown, V. Grimm, R. Meyer, C. Montañola-Sales, P. Ormerod, H. Root, and F. Squazzoni. "Different Modelling Purposes". In: *JASSS* 22.3 (2019), p. 6. issn: 1460-7425.

[2] V. Grimm, U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, *et al.* "A standard protocol for describing individual-based and agent-based models". In: *Ecological modelling* 198.1-2 (2006), pp. 115–126.

Appendix C: Learning Mechanism

To implement the learning mechanism introduced in Section 6.4.1 and mentioned in Proposition 2, this study relies on a reinforcement learning algorithm. Specifically, Q-learning [1, 2] was chosen given it enables agents to develop information collection preferences over time through a series of information collection activities, as introduced in Proposition 1. The following formula is used to update the expected reward resulting from collecting information from each of the agents' contacts.

$$Q(s_t, a_t) \leftarrow (1 - \alpha) \cdot Q(s_t, a_t) + \alpha \cdot R(s_{t+1}, a) \tag{1}$$

Where:

- $Q(s_t, a_t)$ = expected reward for the action a (collecting information from a particular contact) at a given observed state s of the environment (responding to a disaster). In practice, Q represents the extent to which the agent expects that a particular contact will provide information that can address its information needs.

- α = learning rate determining the relative importance of the quality of the new information provided by contacts compared to the quality of the information provided so far by the contacts.

- $R(s_{t+1}, a)$ = actual reward obtained by the agent through carrying out the information collection action a given its information collection state s. In this study, this reward is 1 when the collected information addresses the collecting agent's information needs, and 0 otherwise.

The agents are assumed to be myopic, meaning that they do not consider the strategic pursuit of long-term high rewards. Rather, the agents simply consider current rewards in their learning process. As such, the value of the discount factor is equal to 0 (and thus not displayed in the equation above).

An agent's *information collection preferences* are represented by the probabilities of the agent choosing each of its contacts as its information collection source. Such probabilities are computed for each contact as the ratio of the Q value associated with the contact, divided by the sum of all Q values associated with all of the agent's contacts. As such, a higher Q value (expected reward) compared to other contacts, entails that the agent will be more likely to choose such contact among the others when collecting information.

REFERENCES

[1] C. J. Watkins. “Learning from Delayed Rewards”. In: *PhD thesis, Cambridge University, Cambridge, England* (1989).

[2] C. J. Watkins and P. Dayan. “Q-learning”. In: *Machine learning* 8 (1992), pp. 279–292.

Appendix D: Studying emergent IBSs with different thresholds

Experiment 0 showed that multiple thresholds enable to individuate IBSs candidates that significantly contribute to inter-group information exchange, thus qualifying as emergent IBSs. Further analysis is needed to determine if such different thresholds yield the same results in the study of IBSs emergence. In this case, providing the same results means that the conclusions regarding IBSs emergence remain the same, i.e. the propositions remain supported by experimental results independently from the thresholds adopted.

In this appendix, the data from Experiments 1 to 3 is analysed through six different thresholds deemed adequate to capture emergent IBSs, namely the 30th, 40th, 60th, 70th, and 80th percentiles in the FEs distribution (Cf. Experiment 0 - Results Section). The following paragraphs compare the results obtained with these thresholds for each experiment. The appendix considers only the number of emergent IBSs and not their effectiveness in fostering inter-group information exchange. This is because IBSs effectiveness is independent from the threshold adopted and remains the same as detailed in Sections 6.7.2, 6.7.3, and 6.7.4..

Figure 1 shows the results of Experiment 1 and illustrates a comparison between the influence of LN compared to RC on the emergence of IBSs when adopting different thresholds. Despite quantitative variations, LN consistently produces more IBSs than RC, thereby supporting Proposition 1 regardless of the threshold used.

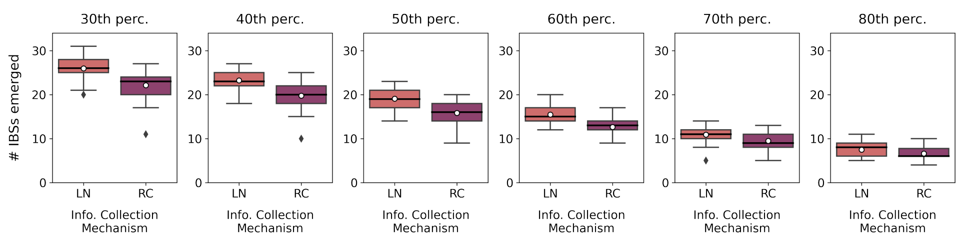

Figure 1: Experiment 1: comparison of the number of emergent IBSs obtained with different thresholds ranging from the 30th (first figure on the left) to the 80th (last figure on the right) percentiles for the two information collection mechanisms LN (LearNing) and RC (Random Collection).

Figure 2 presents the results of Experiment 2, comparing the number of emer-

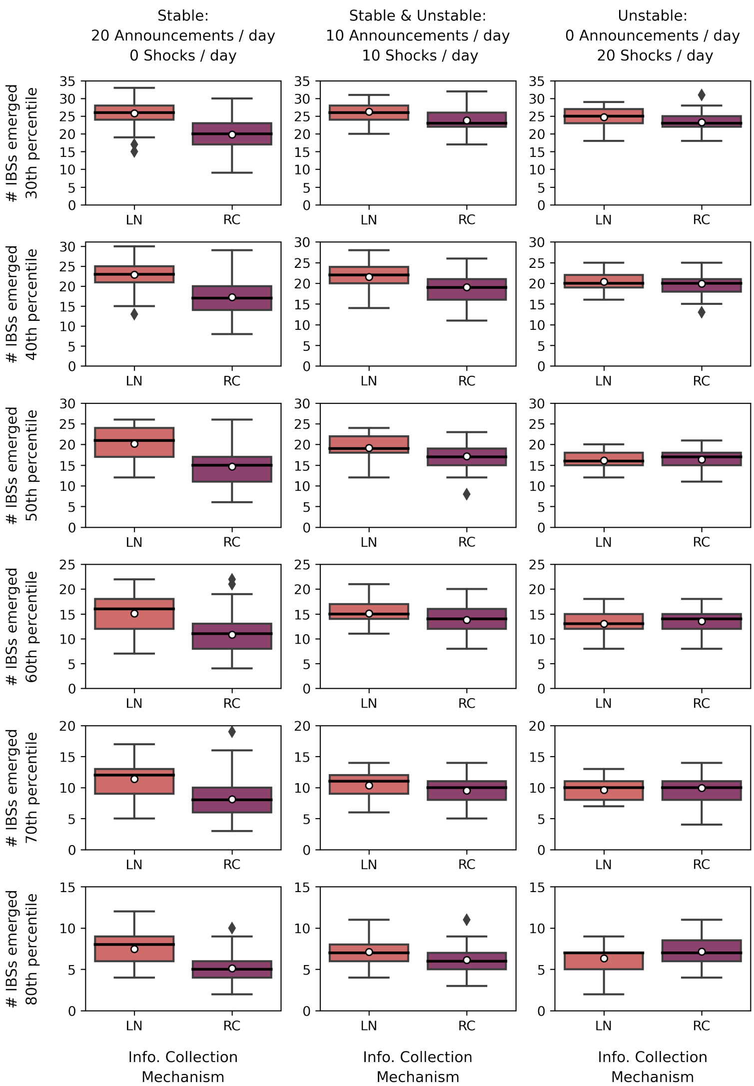

Figure 2: Experiment 2: comparison of the number of emergent IBSs obtained for LearNing (LN) and Random Collection (RC) with the 30th, 40th 50th, 60th, 70th, and 80th percentiles (each represented by one row) and different numbers of stable and unstable information becoming relevant for the groups during each day of simulation (captured in the three columns). While the composition is different, the total number of daily relevant information remains constant at 20 pieces of information per day.

gent IBSs observed with different thresholds for RC and LN when varying the stability of the information origin. In the figure, each row represents the results obtained with one threshold, while the columns represents varying levels of stability, namely stable (only announcements), a combination of unstable and stable (both announcements and shocks), and unstable (only shocks) information. As can be observed by comparing the figures in each row from the from left to right, an increasing number of shocks (unstable information origin) compared to the number of announcements (stable information origin) reduces the impact of learning on fostering the emergence of more IBSs. This observation supports proposition 2 and holds across all thresholds.

Further, with only unstable information (right column), learning minimally impacts the number of emerged IBSs, with effects varying by threshold. From the 40th to the 70th percentiles, LN has no significant influence on IBS emergence. However, the lowest and highest thresholds (respectively the 30th and 80th percentiles) produce different and conflicting results. Precisely, with the 30th percentile, LN increases IBS emergence, but with the 80th percentile, this effect reverses. In this case, these discordant results are considered outliers and disregarded for two reasons. First, they lead to opposite conclusions, likely because they are the most extreme among those found to be adequate. Second, all of the other thresholds (four out of six) consistently produced similar results, confirming that the discrepancies observed with the 30th and 80th percentiles are due threshold selection rather than experimental data. Consequently, results from the 30th and 80th thresholds are excluded. The remaining findings from the 40th, 50th, 60th, and 70th percentiles consistently indicate that learning has no impact on the emergence of IBSs with unstable information origins, supporting Proposition 2.

Finally, Figure 3 presents the results of experiment 3 and shows a comparison in the number of emergent IBSs with LN and RC for varying levels of environmental turbulence and inter-group ties. This figure illustrates that for all thresholds the number of IBSs emerged grows with the number of inter-group ties and the level of environmental turbulence. Further, the number of IBSs emerged is not significantly affected by the information collection mechanism adopted. These findings support proposition 3 and are evident independently from the threshold adopted.

This appendix demonstrates that using various adequate thresholds, as established in Experiment 0, leads to consistent conclusions across Experiments 1 to 3, supporting Propositions 1, 2, and 3 regardless of the threshold used. It highlights the importance of comparing and assessing the consistency of findings across different thresholds when using the method to study the emergence of IBSs. This is necessary as, in specific instances like the 30th and 80th percentiles in Experiment 2, different thresholds may yield conflicting results. Such discrepancies can lead to reconsider and revise conclusions regarding the emergence of IBSs. In this case, the discordant results with the 30th and 80th were considered outliers and disregarded given their extreme values and inconsistent results with the majority of the other thresholds. Therefore, the conclusions of Experiment 2 remained unchanged.

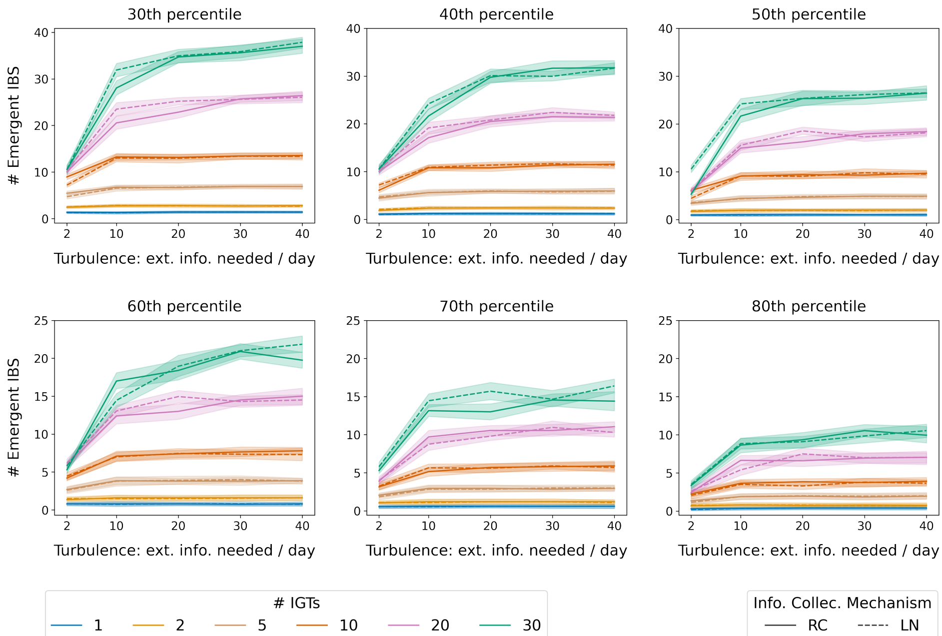

Figure 3: Experiment 3: comparison of the number of emergent IBSs obtained with LearNing (LN) and Random Collection (RC) for the 30th, 40th, 50th, 60th, 70th, and 80th percentiles, different levels of Turbulence, and numbers of Inter-Group Ties (# IGTs).

About the author

Vittorio Nespeca is an engineer and computational social scientist born on March 25th, 1988, in Bologna, Italy. After completing a science-oriented high school, he studied Environmental Engineering at the Marche Polytechnic University in Italy. During his engineering studies, he became fascinated with using models to analyse complex phenomena and support decision-making in socio-technical-environmental systems. To improve his skills in this field, he applied for and was awarded two Erasmus scholarships. These allowed him to study and conduct research at Tampere University of Technology and Aalto University in Finland, where he specialized in using models to support sustainable urban planning.

Once completed his Master's degree in Environmental Engineering in 2014, Vittorio sought to deepen his knowledge of modelling, particularly in the water domain. He pursued a second MSc in Hydroinformatics at IHE Delft in the Netherlands. While he thoroughly enjoyed the technical challenges and the combination of water management, engineering, computer science, and modelling that the program offered, he missed engaging with the social dimensions of systems, which play a crucial role in shaping the behaviour of socio-environmental-technical systems. He became particularly intrigued by how communities and professional response organisations collaborate during floods. For his thesis at IHE Delft, he developed coordination and information-sharing mechanisms to support this collaboration. He implemented these mechanisms in a website and smartphone app, which he tested in real-life disaster simulations. This experience motivated Vittorio to pursue and secure a PhD position at the Faculty of Technology, Policy, and Management at TU Delft.

During his PhD, Vittorio designed and applied methodologies to develop agent-based models through qualitative inquiry. These models were instrumental in studying information exchange between communities and professional response organisations during flood responses. He then continued this line of research as a postdoctoral fellow at the Computational Science Lab at the University of Amsterdam, further advancing his understanding of disaster resilience and collective intelligence. These concepts became central to his work, which focuses on exploring synergies between collective intelligence and disaster resilience. His goal is to design innovative information-sharing strategies, coordination mechanisms, and participatory modelling techniques that harness these synergies to build more resilient societies. He is currently applying this perspective to Public Administration.

Outside of work, Vittorio enjoys cooking Italian dishes with a 'twist,' inspired by the wonderful people, cultures, and flavours he encountered during his time as an expat.

List of Publications

1. Peer-reviewed publications:

6. V. Nespeca, T. Comes, and F. Brazier. “A Methodology to Develop Agent-Based Models for Policy Support Via Qualitative Inquiry”. In: *JASSS* 26.1 (2023), p. 10. issn: 1460-7425. doi: 10.18564/jasss.5014

5. V. Nespeca, T. Comes, and F. Brazier. “A Methodology to Develop Agent-Based Models for Policy Design in Socio-Technical Systems Based on Qualitative Inquiry”. en. In: *Advances in Social Simulation*. Ed. by M. Czupryna and B. Kamiński. Cham: Springer International Publishing, 2022, pp. 453–468. isbn: 978-3-030-92843-8. doi: 10.1007/978-3-030-92843-8_34

4. V. Nespeca, T. Comes, and F. Brazier. “Share: bottom-up disaster information management v1.0.0”. en. In: *CoMSES Computational Model Library* (Dec. 2022). doi: 10.25937/3dbz-qv52

3. V. Nespeca, T. Comes, K. Meesters, and F. Brazier. “Towards Coordinated Self-organization: An actor-centered framework for the design of Disaster Management Information Systems”. In: *IJDRR* 51 (2020), p. 101887. issn: 2212-4209. doi: 10.1016/j.ijdrr.2020.101887

2. K. Meesters, V. Nespeca, and T. Comes. “Designing Disaster Information Management Systems 2.0: Connecting communities and responders.” In: *ISCRAM*. 2019

1. V. Nespeca, K. Meesters, and T. Comes. “Evaluating Platforms for Community Sense-making: Using the Case of the Kenyan Elections”. In: *ISCRAM*. 2018

2. Submitted publications

6. V. Nespeca, T. Comes, and F. Brazier. “Learning to connect in action: Measuring and understanding the emergence of boundary spanners in volatile times”. In: *arXiv preprint* (Under review). url: https://arxiv.org/abs/2405.11998

5. V. Nespeca, R. Quax, M. G. Rikkert, H. P. Korzilius, V. A. Marchau, S. Hadijsotiriou, T. Oreel, J. Coenen, H. Wertheim, A. Voinov, *et al.* “Towards participatory multi-modeling for policy support across domains and scales: a systematic procedure for integral multi-model design”. In: *arXiv preprint* (Under review). url: https://doi.org/10.48550/arXiv.2402.06228

4. T. Oreel, V. Vasconcelos, H. Wertheim, E. Rouwette, R. Quax, V. Nespeca, S. Hadijsotiriou, J. Coenen, V. Marchau, and M. Olde Rikkert. “Measuring health system resilience during the COVID-19 pandemic using dynamic indicators of resilience.” In: (Under review)

3. S. Hadijsotiriou, T. Oreel, V. Marchau, H. Korzilius, J. Coenen, V. Nespeca, E. Rouwette, V. Vasconcelos, R. Quax, and M. Olde Rikkert. “Performance measures of resilience during a pandemic – the case of healthcare and education in the Netherlands”. In: (Under review)

2. S. Hadijsotiriou, J. Coenen, H. Korzilius, V. Nespeca, T. Oreel, H. Wertheim, E. Rouwette, V. Vasconcelos, R. Quax, V. Marchau, and M. Olde Rikkert. “Identifying key complex relations between education and healthcare in the Netherlands during a pandemic”. In: (Under review)

1. J. Coenen, H. Korzilius, S. Hadijsotiriou, T. Oreel, H. Wertheim, E. Rouwette, V. Marchau, V. Nespeca, V. Vasconcelos, R. Quax, and M. Olde Rikkert. “Resilience of coupled systems under deep uncertainty and dynamic complexity: A systematic review”. In: (Under review)

3. Work in progress

3. V. Nespeca, T. Comes, and F. Brazier. “Learning to share the information burden: Load distribution, centrality, and effectiveness of emergent boundary spanners in volatile conditions”. In: (Work in progress)

2. V. Nespeca and K. Yesilkagit. “Toward modeling the impact of organizational structure on collective intelligence in public administration during crises”. In: (Work in progress)

1. F. Oetker, V. Nespeca, T. Vis, P. Duijn, P. Sloot, and R. Quax. “A framework for developing quantitative agent-based models based on qualitative expert knowledge: an organised crime use-case”. In: (Work in progress)

4. Other publications

7. E. Johansson, V. Nespeca, M. Sirenko, M. van den Hurk, J. Thompson, K. Narasimhan, M. Belfrage, F. Giardini, and A. Melchior. “A tale of three pandemic models: Lessons learned for engagement with policy makers before, during, and after a crisis”. In: *RofASS* (2023)

6. V. Nespeca, K. Meester, T. Comes, L. Piccolo, G. Burel, A. Aker, and D. Maynard. *Results of second COMRADES platform evaluation*. en. Deliverable of the COMRADES EU project D 2.4. Delft University of Technology, 2018

5. V. Nespeca, K. Meester, L. Piccolo, A. Aker, G. Burel, T. Comes, and D. Maynard. *Results of third COMRADES platform evaluation*. en. Deliverable of the COMRADES EU project D 2.5. Delft University of Technology, 2018

4. V. Nespeca, T. Comes, and L. Alfonso. “Information Sharing and Coordination in Collaborative Flood Warning and Response Systems”. en. In: *ISD 2018 Conference Proceedings*. Aug. 2018

3. A. Sebastian, K. Lendering, B. Kothuis, A. Brand, S. Jonkman, P. Gelder, B. Kolen, M. Comes, S. Lhermitte, K. Meesters, B. van de Walle, A. Ebrahimi Fard, S. Cunningham,

N. Khakzad, and V. Nespeca. *Hurricane Harvey Report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Tech. rep. Delft, South Holland, NL: TU Delft, Oct. 2017

2. V. Nespeca, L. Alfonso, H. Schuurmans, and D. Solomatine. “E-Aid: Smartphone and Web Applications for Community-Based Disaster Management in Accra”. en. Master’s Thesis. IHE Delft, Institute for water Education, 2017

1. V. Nespeca, E. S. Malinverni, J. Kadlec, and A. Jolma. “A Geospatial Tool for Mapping Urban Ecosystem Services: Contribution to a Land Use Planning Decision Support System. A Semi-Quantitative Analysis for the City of Lahti, Finland”. en. Master’s Thesis. Aalto University and Università Politecnica delle Marche, 2013